Public Health Engineering

A TEXTBOOK OF THE PRINCIPLES
OF ENVIRONMENTAL SANITATION

BY the Late EARLE B. PHELPS

PUBLIC HEALTH ENGINEERING
STREAM SANITATION

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VOLUME I

Part One The Air Contact

With a Chapter on Insects and Insect Control
by Harry D. Pratt, Scientist, U. S. Public Health Service

Part Two The Water Contact

In Collaboration with
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Preface

The title adopted or inherited by a professional group is not necessarily descriptive. The actual field of activity of the civil engineer, for example, is much more restricted than its ill-fitting title would suggest. Similarly, the sanitary engineer, through his textbooks and his professional activities, has defined and delimited his field, not as the engineering of sanitary science, but as the engineering of water supply and its complement, sewage disposal. Thus, despite the laudable efforts evident in some of our colleges to broaden the educational foundation of sanitary engineering, the accepted current usage of the professional title itself implies no such broad coverage of the field of environmental sanitation as is dealt with in the present text.

In 1924 I compiled and published, under the title *Principles of Public Health Engineering,* a series of lectures which had been prepared for a summer-school course at Columbia University. That title, as a subject of instruction, was novel and somewhat provocative.

The American Public Health Association had in 1911 organized its public health engineering section in recognition of the need for a meeting place for that rapidly growing group of engineers who were utilizing their specialized training and techniques in the public health field.

At about the same time the United States Public Health Service had begun the organization of its own engineering staff, variously assigned to work on mosquito control, stream sanitation, and the investigation of epidemic outbreaks of disease. The title *sanitary engineer,* established through civil-service classification, was maintained in the Public Health Service during the subsequent years when that engineering personnel was building its fine record of accomplishment in such additional and diversified fields as milk sanitation, industrial hygiene, ventilation, and illumination. However, the Public Health Service gave early recognition to this broadened field of engineering activity in its publication, inaugurated in 1921, *Public Health Engineering Abstracts.*

At the present time the public health engineer, through his own merits, has gained a substantial place and recognition in public health. Many states and cities have officially established positions in the various grades of Public Health Engineer; civil service and merit systems have set up corresponding classifications; and the engineering colleges are responding in increasing numbers with course offerings in this emerging division of the sanitary engineering section.

The present text has been prepared with this situation in mind. Like its forerunner, it deals with principles rather than with engineering practice. It is written primarily for the engineer who presumably has learned how to design and build, to teach him, in the light of present-day knowledge of sanitary science, what to design and build and why.

Its approach is through chemistry and the biological sciences, especially bacteriology and physiology. It stresses public health through engineering rather than engineering itself. This approach makes the text of service also to the medically trained student of public health. One who may be called on to administer a health department will profit if his basic training includes a somewhat broader treatment of environmental sanitation and its underlying principles than is currently to be found in available public health texts.

During the nearly quarter century that has elapsed since the publication of my *Principles of Public Health Engineering,* the subject has been continuously expanding from within. So great has been the elaboration in the several diverse fields of sanitary science that I have found it needful to seek the collaboration of others in the preparation of an authoritative text.

In the preparation of Part One, the Air Contact, I have been fortunate in being able to secure the aid of Doctor Harry D. Pratt, Scientist, U. S. Public Health Service, whose extensive experience has been utilized in the writing of the chapter on Insects and Insect Control; and we are both indebted to Professor John M. Henderson of the School of Public Health, Columbia University, for reading this chapter and for revising the section dealing with drainage.

Professor C. J. Velz has collaborated in the preparation of the whole of Part Two, the Water Contact; in particular, he is responsible for the development of the systematic outline of principles applicable to both water and sewage treatment, presented in Chapter 13, as well as for the succeeding chapters dealing with treatment of polluted waters and for the chapter on Rural Sanitation.

The necessary expansion of the text into two volumes has obvious disadvantages, and the publisher's suggestion of this arrangement was at first received with some concern. However, there are certain compensations, particularly in that one or the other part is available for use in courses that are correspondingly limited. To this end the two volumes have been made mutually independent as far as may be, with a minimum of cross references and separate indexes.

Earle B. Phelps

May 1948

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CHAPTER 1

MAN AND HIS ENVIRONMENT

INTRODUCTORY

Man has been said to be a product of heredity and environment. Heredity represents an endowment from the past, an ancestral estate to which each individual falls heir at birth and which he must accept whether it be good or poor, to do with what he will. Environment represents the present-day opportunity to develop that endowment, to make good use of a poor inheritance or poor use of a good one. However seriously biologists may debate the relative importance of these two factors in the development of mental and moral traits and of character, it is quite plain that in regard to physical health and well-being there is no hereditary endowment so good that it cannot be wasted away in a bad environment, and rarely one so bad that it cannot be reclaimed, in part at least, by favorable treatment.

This is so because life itself is fluid. That which we sometimes term the stream of life is similar in many respects to a stream of water. Regardless of its source and early history such a stream adapts itself to the varying physical contours of its banks and moves sluggishly or feverishly according to the slope of its bed. It may become fouled by passing over filth and be restored to cleanliness and purity under the influence of air and sunlight. So it is with physical life; confined within fixed boundaries and urged by the very laws of its being to move along established channels, it is nevertheless molded and directed, stimulated or retarded, contaminated or purified by its contacts.

In less imaginative but more concise and descriptive phrases the great biologist, Herbert Spencer, spoke of life as being characterized by a continuous adjustment of internal to external relations, or, in modern terms, by adaptation of function to environment. The degree of this adaptability is great. We see it illustrated, for example, when men, presumably made of the same protoplasm, are found existing in apparent comfort and well-being both under the direct rays of the tropical sun and far within the Arctic Circle; under conditions of extreme poverty and deprivations and under those of luxurious wealth; in the dampness and darkness of a mine, far beneath the earth's surface, and at such mountainous altitudes that the actual atmospheric pressure is reduced by nearly one half its normal value. In fact, if we view life as a whole, there seems to be almost no limit to its adaptability to environmental conditions. The sperm whale in the depths of the arctic sea and the bird of paradise in the tropical forest are merely suggestive of these possibilities.

Our present interest, however, centers upon the human species and not so much upon the limits of its adaptability as upon that other important characteristic, the most favorable or optimum condition. We cannot expect human existence to function best under any of the extreme conditions to which allusion has been made. In whatever direction we may extend our search we always find, between the extreme limits of adaptability within which life may actually exist, a certain much more restricted range where the life processes function most smoothly, and with least danger of overstress and breakdown. This is the range of conditions within which the forces of evolution appear to operate most effectively, because least disastrously, and where progressive improvement, rather than mere static existence, seems to be really worth while. It is one of the major problems of public health to investigate and to define, as far as practicable, this optimum range of conditions. We must learn, not only to determine and avoid those conditions that are definitely harmful, but also to seek out and utilize those that are beneficial.

But we go even further than this. We are today very largely in control of our environment. It is possible, for example, to provide an atmosphere of any specified physical properties within the home or factory. Engineering research and skill have made it possible for us to hear the human voice halfway around the world, to invade the special environments of the fish and the bird, and, by transportation and refrigeration to bridge time and distance and bring the world's foods to our kitchens.

This situation is, of course, limited by the temporary limitations of engineering skill. But it is limited also by our own lack of knowledge. Just as we must know what air conditions are desirable for health and comfort before setting up the equipment to provide them, so, in general, we must know the optimum conditions of living before putting into effect the machinery of control.

The public health engineer of today, is, in brief and to a large and increasing extent, developing the complement of Spencer's definition of life and continuously adjusting external to internal conditions. Our present inquiry then takes this form: What are the important contacts with the environment as they affect the health of man; what are the undesirable and what the most favorable conditions of the environment at these points of contact?

The actual physical environment is made up of a multitude of separate units, none of which is capable of individual existence, and so the problem of the optimum environment is not capable of a single solution. For example, the respective climatic conditions of northern and southern cities, conditions over which we have no primary control, throw into greater or less prominence many of these artificial factors with which we actually have to deal. The problem of ventilation of schools, which presses most seriously in northern cities, would hardly be a major public health matter in a more equable southern climate. In the preservation of food it is quite obvious that the problems in the North, especially during cold weather, are much simpler than those in the South. Nor is it necessary to compare places of different climates to develop this point. In the matter of clothing, an environmental factor of some importance, the most suitable apparel may, within a brief period, and within the same city, be variously a raincoat, a topcoat, or a Palm Beach suit.

The most favorable condition of temperature, furthermore, is dependent upon the occupation of the individual, whether he be engaged in hard manual labor or occupying the easy chair, shall we say, of a public health official. Examining the problem still more minutely, we find that even among individuals, at the same time and place and under apparently the same physical conditions, there is variation of requirements. In our northern cities the disagreement among members of the family as to the proper household temperature is a proverbial matter, and within any group there are innumerable individualities, possibly remnants of heredity, which make for characteristic personal preferences as to food, clothing, and other physical contacts with the environment. Our study, then, must take full cognizance of these manifold individual differences, in addition to the mutual interrelation of the various items which go to make up the environment *in toto*. We can hope, at best, to locate upon this confused chart average conditions and limited ranges, sufficiently broad to include normal individual variation and sufficiently restricted to establish regions that are best suited to the general welfare and development of the group.

ADAPTATION AND TOLERANCE

It has been noted that, in an evolutionary sense, adaptation has been the response of the organism to environmental conditions and their changes. Evolutionary adaptations, however, involve evolutionary times, extending through the ages, and thus do not come within the practical range of our present studies. Adaptation has also a secondary significance in which we are more immediately interested. We speak of a person being adaptable to changes in social or working conditions; of the slum dweller having become "used" to his surroundings; or of persons from the middle latitudes being acclimatized to tropical climates. We adapt ourselves naturally and with little effort to normal seasonal changes, to good weather and bad, to day and night. We tolerate, temporarily, the conditions of an overcrowded streetcar, loss of sleep, and even lack of food and drink.

ADAPTATION. Adaptability, as thus used, implies the ability to adjust oneself rather promptly and without undue effort or unfavorable response to changed conditions. The changes may be of a permanent nature, such as are associated with migration to a new country, or of a reversible and periodic nature, such as seasonal changes in temperature. The resulting adaptation or adjustment to the change may itself be permanent, or it may last for only a limited period.

Acclimatization or "getting used" to new conditions implies a more definite initial reaction to the change but one which can be satisfactorily made and sustained. It also implies permanency of a sort, although such an acclimatization as that of the European to the tropics is recognized, in general, to be a limited tolerance, and becoming accustomed to extreme poverty in no way suggests that a low standard of living is desirable or best.

TOLERANCE. Tolerance is a phenomenon of the same order, but having a somewhat different and more suggestive meaning. In engineering, it is a well-defined word indicating the acceptable limits of departure from a given or desired dimension.

Biological tolerances have a similar meaning. Optimum conditions may be conceived, but, owing to limitations of physiological experimentation, they can be measured only within a certain range. Moreover, even if the optimum could be accurately defined, it is not generally feasible, nor is it necessary, to provide it exactly or at all times. Tolerance in biology defines the range about the optimum within which the organism is enabled to carry on its normal functions.

Biological tolerance has one unique characteristic. In general, it is a time–intensity function. One may, for example, sustain continuous exposure to the toxic effects of carbon monoxide in a certain minimal concentration without harmful effect. With increasing concentration of the poison, the time of exposure permissible with safety decreases continuously. This is rather typical of tolerance and brings it into line with acclimatization. Life for the European in the tropics, for example, is often found to be merely a limited tolerance over a period of a few years, after which a return to the homeland is found desirable.

Finally, adaptation to adverse conditions may increase the normal tolerance range or extend its time. Workmen in the digester room of a sulphite pulp mill are continuously exposed to a concentration of sulphur dioxide gas in the atmosphere, which is exceedingly painful and even unbearable to the casual visitor. Whether this increased tolerance, through adaptation, is permanent or has its own time limit could be determined only by a compilation of the health and mortality statistics of such a group.

THE RULE OF THE MEDIUM. Professor Ellsworth Huntington in his *Civilization and Climate** discusses the effects of the environment upon mankind and develops what may be called the law of the medium. When civilization is viewed as a whole, it is seen that man has progressed most rapidly through the ages, not in the regions of extreme cold nor in those of high temperature, to both of which he has become adapted racially, but rather in the zones of medium temperature. Similarly, neither the dryness of the desert nor the excessive wetness of the swampy jungle, but a moderate amount of rainfall, appears to favor the development of the race. Finally, even in the matter of variability itself, the rule of the medium holds. A moderate amount of variability in the matter of temperature or of storminess is superior to excessive and sudden changes over wide

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* The more important reference works cited may be found listed at the end of each chapter.

ranges, as well as to the steady monotony of such climates as those of the South Sea Islands.

Such a conclusion is quite in harmony with the general facts of evolution. Development of an adaptability to a given range of conditions must indicate least favorable conditions at the extremes and an optimum condition somewhere near the middle of the range. It is a matter of common experience that medium conditions and times, the morning and the evening, the spring and the fall, the periods of gentle showers and of light breezes yield the maximum comfort and pleasure. In brief, the rule of the medium seems to be a most satisfactory guide to optimum physical and climatic conditions.

PUBLIC HEALTH

BIOLOGICAL ASPECTS. Public health deals largely with the problems of man's relation to the environment. Its task is to assure the necessary favorable contacts and to minimize the unfavorable. Its problems are manifold, and to their solution it brings the resources of many of the fundamental branches of science.

At the very foundation of the public health structure lie the biological sciences, especially physiology and bacteriology. The life processes are found to conform to many of the same laws and principles that operate among the physical and chemical reactions of the inorganic world, and physics and chemistry have assumed places of ever-increasing importance in biological investigations. These investigations, in turn, are providing a growing fund of knowledge concerning the reactions of living things to the most varied of environments, and it is thus becoming possible to determine the most favorable conditions for the health and well-being of the human species and the least favorable ones for the activities of man's enemies.

These are the biological aspects of public health. As they deal largely with the fundamental data which go into the teaching of medicine they are often called the medical aspects. To a very considerable extent, the study of human reactions to the environment corresponds with Spencer's definition of life. It is a study of the *adjustment of internal to external relations.*

But public health goes beyond this. It recognizes that there may also be an adjustment of external to internal relations, that is, an adaptation of the environment to man by control and modification of his physical and biological surroundings. In truth, this is the older phase. Man took refuge in his first crude shelters and built his first fires long before he gave any heed to his own marvelous powers of adaptation.

Modification of the environment is, in fact, the complementary reaction of adjustment to the environment. The immediate air environment of a warm-blooded animal, for example, is continuously modified by being warmed. The life processes and the environment meet each other part way at every contact. But beyond this there is, in modern life, an actual control of the environment—a planned and enforced change of major proportions. Examples of this are seen in housing, heating, lighting, and similar works.

PUBLIC HEALTH PRACTICE. Doctor Haven Emerson, an eminent practitioner and teacher of public health (and a friend and counselor of the author's over many years), has broadly but concisely defined the practice of public health as *the application of the sciences of preventive medicine, through government, for social ends.*

The sciences of preventive medicine are of wide range, but their application involves two major principles, the study of causes and the study of preventive measures. If, perchance, it includes curative remedies, the third and most conspicuous part of medical science, these may be justified, as public health practice insofar as they cure *for social ends,* that is, for the protection of the public.

PUBLIC HEALTH ENGINEERING. The knowledge and application of those preventive measures with which sanitary science is so largely concerned take us into regions that are engineering, rather than medical. This, however, must be noted as the characteristic nature of all such activities. Their basic data are the data of the medical sciences. They, too, rest upon a study and knowledge of causes. Only when these are understood may we profitably undertake the study and application of engineering techniques in prevention.

The history of typhoid fever and its relation to water supply and to food will provide a useful illustration of the role of the public health engineer. Biologists have learned that typhoid fever has its origin in a specific germ derived from the excreta of a pre-existing case of the disease, active or latent, and taken into the alimentary tract of the victim. The habits and reactions of the typhoid organism, *Eberthella typhosa,* have been rather thoroughly investigated. It has been learned that it frequently passes from victim to victim through the medium of water or food; that it tends to die out under the unfavorable environments of soil or water, although its death rate is not so rapid as to insure against the passage of some surviving organisms down a stream to a waterworks intake or through the soil to a well; that it multiplies in foods, especially in milk, and at a lower rate at lower temperatures; that it can be destroyed by heat and by various chemical substances.

This fundamental knowledge makes it possible for the individual to protect himself by taking certain precautions, such as thoroughly heating everything that is taken into the mouth. But public health implies much more than this. Because of lack of understanding, indifference or carelessness, the individual cannot be relied upon to apply the necessary preventive measures, and his relation to the public in the case of an infectious disease makes it a matter of public concern that he be protected *through government and for social ends*. Public water supplies, milk supplies, and other food supplies are readily subjected to public control, which can be made more thorough, efficient, and economical than individual control.

In this field of control the engineer plays a leading part. He finds that the natural purifying powers of the soil can be directed and controlled and even vastly improved by the employment of suitable engineering structures, and thus he develops methods for the treatment of water and sewage. For greater efficiency and economy he employs the known principles of chemical coagulation and chemical disinfection, again using engineering skill to direct and control the natural forces and agencies to the required end. In the case of milk supply these remedies are not available, but there are other possibilities. The combination of time and temperature necessary for disinfection having been specified, the engineer designs and operates machinery and plant equipment for heating or pasteurizing milk and for its handling on a commercial scale, to the end that the milk supply may be safeguarded.

This specialized field, in which engineering principles and techniques based upon biological data are employed in the practice of public health, constitutes the field of *public health engineering*. It deals essentially with the control of the environment, with those modifications and protective and preventive measures that have been found desirable or necessary for providing optimum conditions for health and well-being. It is synonymous with *environmental sani-*

tation and represents the practical application of *sanitary science.*

The differentiation of public health activities into their biological or medical and their engineering branches does not apply so much to the routine administration of these activities as it does to the more fundamental study and development of basic principles, which we term research and design. No one without bacteriological training and experience is qualified to determine the thermal death curves of the pathogenic bacteria likely to be found in milk; likewise sound engineering is equally essential in the design and control of pasteurizing machinery which will, with certainty, subject each particle of the milk stream to the specified destructive combination of time and temperature. But in the routine control of the process of pasteurization, as a part of the broader problem of the control of the milk supply, there is required merely a basic knowledge of the scientific principles that have been developed and a training which will enable the official in charge to recognize the essentials. Although this requirement is far less than the sum of the requirements of the investigators and designers, it is in itself, because of its breadth and complexity, a matter worthy of our serious study.

Engineering has been defined as the art of directing the forces and activities of nature to the use and convenience of men. Confining the attention to those *forces* and *activities* which are included in the *sciences of preventive medicine* and to the direction of those forces and activities *through government and for social ends* leads to an appropriate delineation of the field of public health engineering.

It is our task in the chapters which follow to explore the various subdivisions of this field with the object of studying, first the biological facts and factors which underlie each specific problem of environmental control and, second, the physical and engineering principles that have been or may be employed in its solution.

THE ENVIRONMENT SUBDIVIDED

FAVORABLE CONTACTS

AIR, WATER, AND FOOD. The principal reaction of animal life, looked at in a purely chemical sense, is oxidation. The necessary conditions for this reaction are a supply of oxygen, an aqueous medium to hold the reagents in solution, and organic matters capable of undergoing oxidation along certain restricted lines. Thus air, water, and food are the primary requisites of animal life and constitute the three essential channels of communication between the living organism and its environment.

It was pointed out many years ago by Mrs. Ellen H. Richards that, in man, the necessity for a continuous contact with each of these three environmental agencies varies in the order given. His storage capacity for air is small, and suffocation results if his contact with the air environment is cut off for only a few minutes. Water can be dispensed with for some days, and a 40-day fast is not an unknown event. These time relations are of more than incidental interest, for they are related to and doubtless determined by the availability of the supply and man's consequent adaptation.

Air is continuously available, and in quantities greatly in excess of normal requirements. Capacity for storage would be without value except, possibly, in a race of pearl divers. By reason of its abundance and ready availability, the air supply is the easiest to control and to adapt to modern conditions of living.

The food supply of man, on the other hand, has only become continuously available through the operation of a highly specialized social organization and, even then, in strictly limited quantities—a fact borne in upon us during these troubled times. Among primitive peoples food supply depends, to a large extent, upon the vagaries of the climate or the fortunes of the hunt. Food supply now constitutes one of the most complex phases of the environment, involving production, handling, preservation, storage, distribution, and preparation, as well as the data of the sciences of nutrition.

Water supply occupies an intermediate position. As a rule, water is readily available in habitable regions, but neither continuously so, nor in such excessive quantities as is air. The problem of its control is likewise intermediate in complexity. It involves in its simpler aspects storage, to provide for periods of drought, and distribution. We shall later see that man's use and impairment of natural water supplies further complicate this situation.

OTHER FAVORABLE CONTACTS. There are other contacts or channels of communication with the environment, not essential to life perhaps, but of great practical importance to well-being. These will claim some attention and may conveniently be classified under one of the major contacts. The environment provides light, the medium for the operation of the sense of sight, and attention must be given to the suitable adjustment of conditions for its proper functioning. Sunlight and certain forms of artificial light also have important relations to certain other physiological activities which are even now just beginning to be understood. The senses of hearing and of smell are other independent channels of contact through the air.

UNFAVORABLE CONTACTS

All these, and possibly others of lesser importance, are the favorable contacts. They are essential to life, or beneficial. In distinction, there are certain environmental factors which are unfavorable and harmful. Against these it is necessary to devise means of protection or defense.

CLIMATIC AND NATURAL. Against unfavorable climatic conditions man has erected shelter and provided clothing and artificial heat. Against darkness, which would curtail his hours of activity, he provides artificial light, and against competitive life of every sort, from the wild beasts of the jungle to the germs of infectious diseases, he employs all the resources of his ingenuity and his ever-expanding knowledge of the natural forces. These may be termed the primary unfavorable factors. They exist independent of human activity.

RESULTING FROM HUMAN ACTIVITIES. There is another group of unfavorable factors that have resulted from the activities of man and in part from his attempts at control. Frequently, as in housing, the solution of one problem introduces several others, such as ventilation and illumination.

Given air, water, and food, the human mechanism is able to carry out its essential oxidizing reaction, the principal purpose of which is growth and the production of useful energy. The final disposition of that energy need not be further considered, but it is necessary to consider the remaining output of the reaction, the by-products or wastes. Chief among these are heat, carbon dioxide, water vapor, and the excreta.

Consider first the relation of certain of these to the simplest and most intimate of the environments, the air. Pollution of the air by the waste products which are exhaled or which pass off through the skin is immediate and unavoidable. The mechanism of respiration could hardly have been better designed to accomplish this result. It is as if, in the water environment, domestic sewage were discharged directly into the water-supply reservoir. Yet, owing to the abundance of the air supply, its great freedom of motion and the ready diffusibility of gaseous substances, no harmful condition is likely to arise in the open. It is only when the air supply is artificially limited by confine-

The pollution of water and of food by human wastes is more serious and less easily remedied. Here the provisions of nature and the physical laws which apply are not so helpful. In fact, they appear to favor the disease-bearing agencies and to facilitate their passage from patient to new victim. This, of course, is merely biological adaptation on the part of the disease bearers. The life history of the malaria organism (p. 193) offers a marvelous example.

One of the major problems of environmental control is to learn as much as possible about these various channels of communication and, by prevention or remedy, to protect man against the pollutions that result from his own activities.

SYNOPTIC OUTLINE

These various aspects of environmental sanitation may now be regrouped so as to bring them under the three major contacts. This grouping, possibly somewhat arbitrary in certain features, provides a useful order of presentation of the subject matter and thus constitutes a synoptic outline of the sections and chapters which follow.

The present text (Volume I) is confined to the discussion of the first two contacts, air and water, leaving for Volume II treatment of food supply and of certain other matters of a mathematical nature.

THE ENVIRONMENT

- The Air Contact
  - Weather and Climate
    - Housing and Clothing
      - Air Supply, Ventilation.
      - Heating.
      - Illumination.
      - Other Services.
  - Atmospheric Pollution.
  - Noise.
  - Insects and Insect Control.
- The Water Contact
  - Water Supply.
  - Plumbing.
  - Sewerage and Sewage Disposal.
  - Stream Sanitation; Other Uses of Streams; Bathing, Shellfish Growing, etc.
- The Food Contact
  - Milk.
  - Shellfish.
  - Other Foods.
  - Markets and Eating Places.
  - Garbage Disposal
    - Rats.

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PART ONE

THE AIR CONTACT

Man's Relation to the Atmosphere

The atmosphere constitutes man's most intimate environmental contact. It presses with a force of about 15 pounds upon every square inch of the body's external surface and, through respiration, it freely bathes the extensive inner surface of the lungs. From there its gases, and especially the life-giving oxygen, are diffused and absorbed into the blood stream in exchange for carbon dioxide, a waste product of the bodily metabolism.

Adverse atmospheric conditions undoubtedly led to the early development of protective shelter, clothing, and housing; and housing, in turn, has resulted in many secondary problems such as ventilation and lighting. The body is cooled by the air contact; a process as essential to normal operation as is the cooling of a gas engine, and carried out in a very similar manner, by means of forced circulation of a heated fluid, the blood, through a "radiator" system, the lungs and skin. This cooling function of the air and the maintenance of a hygienic thermal environment constitute the physical basis and the primary objective of much of our modern air conditioning practice.

The transmission of light for vision and of the thermal, therapeutic, and germicidal radiation from the sun are matters of specific air transparency, and artificial lighting is, in the last analysis, the resultant of supply, transmission and reflection of luminous flux. We may speak, therefore, of a luminous environment, as well as of a thermal environment.

The special senses of hearing and smell likewise function through air-transmitted stimuli and are assailed by noise and by offensive odors. These senses then each have their special air environments.

In brief, there are many normal physiological functions which depend upon the atmosphere as a transmitting or intervening medium or upon environments acting through the air. For these reasons, we shall broaden our concept of the air contact in order to investigate the effect upon health, comfort, and efficiency of such abnormal modifications as smoke, dust, odors, and noise, and of the intensity and distribution of artificial lighting.

Sickness and death may result from pollution of the air with toxic gases, such as carbon monoxide produced in a poorly functioning water heater, or with any of the scores of dusts, fumes, and vapors now known and listed as industrial hazards. Ventilation, especially industrial ventilation, thus involves more than the control of the thermal environment. A certain degree of freedom from impurities of many specific types must be maintained. Nor need these examples of dangerous air pollution be confined to chemical poisons and physical contaminants. Through the air one may encounter air-borne germs of disease recently expelled from an infected nose or throat during sneezing, coughing, or merely speaking. Our survey of the air contact must take note of the renaissance of an ancient theory of air carriage of disease and review that newest of sanitary measures, the disinfection of air.

Finally, air-borne contact with certain diseases may also be established through such biological hosts as mosquitoes or such mechanical carriers as flies. There are many kindred channels of infection by insects, and the means for their control may well be considered as coming within our broadened concept of the air environment.

These in brief outline are the major subdivisions of man's contact with the atmosphere, to be dealt with in some detail in the chapters which follow. It may be well at the outset to survey some of the physical aspects of the atmosphere itself as they appear in the form of weather and climate and in the associated problem of housing.

CHAPTER 2

WEATHER AND CLIMATE. HOUSING

THE WEATHER

That uncertain fluctuating day-by-day combination of temperature, humidity, wind, sunshine, cloudiness, fog, and precipitation, which provides an unfailing subject of conversation, generally adverse, we call the *weather*. It is forever creating, with surprising frequency, new high and low records for the date, the month, the year, or the entire period of observation. Its prediction for tomorrow, or for some longer period ahead, is becoming an increasingly accurate scientific procedure, of great usefulness to agriculture, to commerce, and to the aeronautical art, as well as to the "man on the street."

Perhaps the characteristic of weather having the greatest influence upon health is its quick changes. The slower seasonal changes, like climatic differences, are met by gradual acclimatization and with suitable changes of clothing. Sudden changes, such as accompany a *cold wave,* catch the body unprepared, or the unwary individual without suitable protective clothing. In northern cities physicians often speak of *pneumonia weather;* and the general outbreak of common colds which follows the early cold weather and the starting up of the heating plants is an annual event which never fails to materialize.

CLIMATE

Climate is the more stable long-period set of conditions, stated in terms of averages and normal seasonal ranges, which characterizes places and regions. It determines the nature of agricultural pursuits and the choice of vacation lands and health resorts and furnishes unlimited copy for Chambers of Commerce.

SOME CLIMATIC FACTORS

Climate is determined to a large extent by certain fixed geographical factors, among these being latitude, altitude, and relation to the sea.

Latitude. The latitude of the place influences the solar radiation in several ways. At any point on the earth's surface the sun is above the horizon about half the time; thus the total hours of possible sunshine per year are constant and independent of latitude. But the distribution of these hours varies from the extreme of 6 months of day and 6 months of night at the poles to the nearly uniform 12-hour day at the Equator. The longer days of summer and the longer nights of winter make for more marked seasonal variations in temperature in the higher latitudes.

Again, the intensity of solar radiation, as received upon a horizontal surface, is proportional to the sine of the sun's altitude. For points outside the tropical zone, the altitude of the noon sun, as of any given date, decreases directly with the increase in latitude. This makes for a continuously decreasing rate of effective radiation per hour of actual sunshine and also for a wider range of effective radiation over the seasons as the latitude increases. Finally, it is estimated* that about 32 per cent of the solar radiation, incident upon the earth's outer atmosphere, is lost by total reflection, and that an additional 34 per cent is absorbed within the atmosphere. If we define as unit air mass the atmospheric layer directly overhead, the air mass through which the radiation passes, and which is responsible for atmospheric absorption, is proportional to the cosecant of the sun's altitude, or inversely proportional to its sine. Thus, at the higher latitudes less heat is received; it is spread over a greater area, owing to the angle of incidence, and it is distributed less uniformly throughout the year.

Sky brightness, a condition of direct influence upon natural illumination within buildings (see p. 155) is also a function of latitude. In the continental United States its value appears to decrease about 2 per cent per degree of increase in latitude.†

Altitude. The altitude of a place is a climatic factor because of the lesser air mass overhead. This results first, in a lessened absorption of radiant energy by the atmosphere and consequent greater intensity of solar radiation. The increased warming effect, however, is more than matched by an opposite effect related to the selective transparency of the atmosphere for radiation in different portions of the spectrum. The atmosphere has a blanketing or "greenhouse" effect, because it readily transmits much of the high-temperature

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* *Physics of the Air.*

† H. H. Kimball, *Monthly Weather Rev.*, **47**, 769, 1919.

radiation of the sun but is more opaque to the longer wave lengths which are reradiated from the cooler surface of the earth.

Thus, the higher altitudes are characterized by more intense warming by day and a greater rate of cooling by night. The net effect is a decreased mean temperature with increasing altitude. There are said to be places in Africa and in South America in which there is perpetual snow under the Equator.

Altitude also affects sky brightness. In the Plain states, west of the Mississippi, at elevations between 1500 and 2000 feet, the average brightness of the whole clear sky is about 25 per cent greater than it is in the states along the eastern coast, at elevations under 500 feet. In the Plateau states, west of the Rockies and at elevations of the order of 7000 feet, the sky brightness is about 46 per cent greater than in the East.*

Finally, the mean barometric pressure of a place is determined primarily by its altitude. The relation between the two does not follow the theoretical formula based upon static equilibrium, but within the habitable zone, that is, up to the perpetual snow line at 3 to 4 miles elevation, the pressure falls off at a geometric rate of about 20 per cent per mile. Its relation to the normal sea-level pressure P, therefore, is

$$0.8^{m}P$$

m being the altitude in miles. Thus at Denver, Colo., elevation just one mile, the normal pressure is about 80 per cent of that at sea level, and at the elevation of some of the towns of Peru and Bolivia, three miles, the pressure becomes a little over one-half normal.

Apart from its relation to air currents, pressure *per se* probably exerts little influence upon human well-being. Rapid ascents of high mountains are likely to cause *mountain sickness,* but adaptation takes place quickly, and the only permanent result is a more rapid respiration rate and deeper breathing to compensate for the diminished oxygen pressure.

PRECIPITATION. The average annual rainfall, together with its seasonal distribution, constitutes one of the most important and significant characteristics of climate. Its relation to stream flow and to water supply is so basic as to justify a detailed treatment under Hydrology, Chapter 9. As a climatic factor, it modifies the nature of the vegetation and to a large extent determines the extent of

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* H. H. Kimball, *loc. cit.*

agricultural development. In conjunction with the topography and geology of the region it is responsible for the conditions of soil wetness, the elevation of the water table and the presence of swamps, plains, and forests. It influences animal life from insects to man. It has special significance in the prevalence of malaria and other mosquito-borne diseases.

Some of the effects of the extremes of precipitation in each direction may be modified by irrigation on the one hand and by drainage on the other. By these means large areas in many parts of the world have been reclaimed and made usable. On the whole, however, precipitation largely determines the habitability of the region.

Precipitation is not an entirely independent factor of climate, but rather a resultant of several of the more basic factors. Latitude and elevation modify it as between rain and snow and thus greatly influence the distribution of the effective precipitation through the seasons. Mountain ranges, proximity to major bodies of water, and, in particular, the great circulations of air and water discussed in the next section all contribute to the determination of its extent and seasonal distribution.

CIRCULATION OF AIR AND WATER. Two dominant factors in the determination of climate are the great currents of circulating air and water which move in more or less fixed paths over the earth's surface. The heated air of the tropics rises and flows toward the poles, while a countercurrent of cold air flows from the poles toward the Equator nearer the earth's surface: the rotation of the earth gives to these currents a lateral twist resulting in the northeast and southeast trade winds. Land and water configurations, the physical influence which results in the cooling of rising (expanding) and the warming of descending (contracting) air, and the influence of evaporation and of condensation upon the temperature of the air mass, all combine to produce climatic zones. These may be characterized by moderate to extreme conditions of moisture, drought, storminess, or seasonal variations; by monsoon and hurricane seasons; or by somewhat fixed storm tracts over which the centers of cyclonic storms pass in regular succession. In the temperate zones storms and precipitation result from the mutual interaction of the *cold fronts* of the return currents from the poles and the warmer poleward moving currents.

Corresponding to these air currents are the great ocean currents of which the Gulf Stream is a well-known example. Moving away from the heated tropics, these waters profoundly modify the climates of the lands near which they pass. Other lands are similarly influenced, in the opposite direction, by the return currents from the polar regions.

Masses of water also produce seasonal lags. They delay the onset of spring and early summer and prolong the normal fall into the early winter. These effects result from the mobility and the relatively high heat capacity of water, as compared with that of land surfaces, and the fact that thermal energy penetrates into water and is absorbed in depth. Air circulation tends to equalize land and water temperatures and thus to make the seashore cooler in summer and the seacoast, in general, milder in winter. In the Citrus Belt of Florida the occurrence or nonoccurrence of frosts is frequently determined by the presence of near-by lakes or even of a high underground water table.

Thus, proximity to the sea and to other large bodies of water, such as the Great Lakes, has a marked influence upon climate. In many places, such as the British Isles, relation to the sea is the dominant climatic factor.

MEDICAL CLIMATOLOGY

The relation of climates to man, especially to his health and physical well-being, constitutes the subject matter of medical climatology. These relations have long been matters of observation and of scientific study in the colonial possessions of European countries. Modern means of travel will make them of increasing interest and importance.

In his *Mainsprings of Civilization* Huntington analyzes the conditions of progressive civilization into climate, racial inheritance, and cultural inheritance. Cultural inheritance is the accumulated capital of a people, a measure of past development but not necessarily of future progress. Compare, for example, the "lost" civilizations of Central America, quite conceivably extinguished by unfavorable climatic changes, with the barrenness of the early North American colonists, both in physical establishments and cultural background.

Even racial inheritance is regarded as less fundamental than climate, for climate underlies evolutionary adaptation and is intimately related to health and work, to food resources, and to competitive life. It has determined major migrations, wars and conquests, and racial intermixtures.

Mills ascribes to climate much of man's racial, physical and cultural development. He regards the ease or difficulty of heat loss from the body as the major contributing climatic factor. In the cooler and dryer climates, disposal of the waste heat attendant upon physical labor is readily accomplished, metabolism and physical activity are stimulated, fertility is enhanced, and children grow faster and develop more robust bodies.

"There remains little doubt," says Mills, "that mean temperature levels and ease of body-heat loss does truly dominate human development both regionally and down through the centuries of racial existence."

By a somewhat arbitrary combination of climatic variability, including storminess and diurnal variation, with general temperature level, Mills arrives at an *index of stimulation* for the place which he believes to be highly correlated with basic health. This index, however, is likewise subject to the rule of the medium.

High stimulation is believed by Mills to lead to a high-energy level of living and greater general vitality which may prove too great a strain. He finds that, in the Great Lakes region, "probably one of the most invigorating climates the world has to offer," the degenerative diseases of postmiddle life, arteriosclerosis, diabetes, and mental failure, are more frequent than in the South. Resistance to infection, on the other hand, is increased.

Aggressiveness and forceful advancement are possibly accompanied by a wasteful expenditure of energy and associated with more frequent breakdowns both physical and mental. At the lower level of living, energy is utilized more advantageously. Work is done more slowly, but upon a lesser fuel intake per unit of work done.

Mills sees especial danger in northward migration from the southern states. Such migrants are more susceptible to sclerosis and to metabolic disturbances, more sensitive to chilling, and less resistant to infection. Even a short stay in the tropics renders one from the north more susceptible, upon his return, to colds and pneumonia.

ACCLIMATIZATION. Migration from middle latitudes to the tropics presents many issues of economic as well as of health importance, especially in Great Britain, Holland, and other countries having extensive tropical colonies. Some of the simpler physiological facts appear to be established.* There is a lowering of blood pressure due to dilation of the capillaries. The pulse rate increases temporarily but after a few weeks or months resumes its normal value. Deeper and slightly more rapid respiration brings about increased lung ventilation and assists in heat dissipation, and much more water is drunk to offset increased evaporation.

Martin believes that much of the difficulty of the European in the tropics is a matter of clothing.

> Man, in his nakedness and the wide area over which he can sweat, is the best adapted of all creatures to withstand high external temperatures, and coincident with his loss of hair his increasing intelligence has allowed him to extend the downward range of external temperature at which he can remain homothermic by providing himself with an adjustable insulation . . . the obstacle to work in hot climates for the European, is as much a social as a physiological one. It is clothing. The coolie works with his nice brown body exposed and covered with sweat and is jolly, whereas the white man distressfully labors in a hyperthermic condition, straining his heart to work a refrigerating plant which he has rendered inefficient because his sense of dignity forbids him to expose his skin.

Experimenting with himself, Martin found that, while he was doing hard labor, his body temperature rose directly with the wet-bulb temperature of the air (see p. 42), and as much as 3 degrees Fahrenheit. This he regards as physiological adaptation and not as a failure of compensation. Metabolism is stimulated, in a cold environment, by the activity of the thyroid and other glands, and this same effect is measurable in the higher temperatures as a slightly depressing action upon metabolism. However, the total effect amounts only to about 10 per cent in a resting man, and to about 2 per cent in a man walking at four miles per hour. It is too small, therefore, to be of any practical effect during labor.

MODIFICATIONS OF THE CLIMATE

Throughout the long history of the world, climate has been a geological feature, intimately related to the glacial periods and other geological ages. The desert of Sahara was probably a fertile plain when central Europe was under a sheet of perpetual ice. In our own

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* For a good summary see Sir Charles J. Martin, *Lancet*, 219–561 and 617, 1930—II.

day, careful analysis of the systematic records seems to disclose definite climatic shifts superimposed upon the shorter-time cyclic variations. The records are not sufficiently extensive to show whether these shifts are, in fact, evidence of a continuous drift, or are merely part of long-period cycles.

Unfortunately, or perhaps fortunately, weather and climate are not immediately subject to modification by human interference, despite recent successful experiments with the use of solid carbon dioxide, dry ice, in inducing precipitation over limited areas and times. However, by observation and the application of the data of climatology, something may be learned as to what is beneficial and what harmful in matters of temperature, humidity, wind movement, sunshine, fog, and other meteorological elements, and in their diurnal and seasonal variations.

In a restricted sense all these climatic features are, in fact, modified by housing and clothing, not to speak of travel. Especially important is that artificial climate in which so large a part of our lives is spent, the indoor climate of the house, the shop, the office, and the school. This is not only true during the so-called heating season of the winter months in the North, but is becoming increasingly so, owing to modern air conditioning, during the hot-weather months and in the warmer countries.

An even more personal climate is that which is maintained within the clothing of the individual. Body heat and moisture are retained to a greater or less degree, as desired, and protection is afforded against wind, rain and too intense sunshine. The hygiene of clothing might well be the subject of more complete scientific examination than has often been given to it. Unfortunately, clothing is variously employed for protection of the body, for personal adornment, and in compliance with the normal dictates of modesty. The extent to which one or the other of these functions becomes dominant makes an interesting study in human nature. Clearly, utilitarianism does not control the selection and use of clothing, however simple it may be, nor can it be expected to.

Enclosed and heated trains, streetcars, and automobiles provide temporary artificial climates like those of the home and office, all of which suffer from one defect. Passage from atmospheres that are comfortable, or that are more likely to be uncomfortably overheated, to a raw chilly out-of-doors is attended by a shock that is distinctly unwholesome, just as are sudden changes in weather.

HOUSING

Looking backward through the long vista of human development, it is not difficult to think that the earliest attempts made in the direction of environmental control were those in which protection and security against the rigors of the climate, sunshine and rain, heat and cold, were sought in natural or artificial enclosures. This belief is supported by the many evidences of early cave life among primitive peoples. Today the functions of housing are expanded and differentiated, and there are many distinct types of problems associated with the home, the school, the factory, and the various places of public gathering.

Among these, however, the home, the place of living, of eating, of sleeping, and of rearing the family, is of such basic significance in the social and economic life of the community and in the well-being of its people that the term *housing* in general parlance is limited to the sheltering of the family; to the location, construction, equipment, and maintenance of the home. Curiously, the problems of housing are not so much the meeting of the basic requirements of shelter, as they are those secondary matters that have arisen as a consequence of that attempt: overcrowding, ventilation, lighting, and the provision of facilities for cleanliness and for the disposal of wastes.

Many of these specific problems are common to buildings in general and will call for detailed consideration in the proper places. For the present we deal with those special matters, associated more frequently, but not exclusively, with a still more restricted meaning of the term *housing;* with the homes of the poorer classes in the more crowded portions of every city, with the slums or that district often spoken of as "the other side of the railroad tracks." In brief we deal with minimum requirements for housing the underprivileged as a social recognition of the fact that sickness and death rates in every community increase as we pass down the economic scale.

RELATION TO HEALTH

The obvious point of departure in any discussion of minimum housing requirements is the effect of bad housing conditions upon the health of the inhabitants and, indirectly, upon the community at large. Concerning this, Professor Winslow has written in *Housing for Health:*

> It has so far been impossible to demonstrate by exact statistical procedure what proportion of the high death rates which characterize the slums may be due to the physical characteristics of the slums themselves, what proportion is due to other aspects of the poverty of their inhabitants, and what proportion is the result of inherent physiological and psychical handicaps of the slum dweller.
>
> The Committee on the Hygiene of Housing of the American Public Health Association, in its "Basic Principles of Healthful Housing," has listed thirty specific characteristics of housing whose direct influence upon health has not been successfully challenged.
>
> Is it possible to doubt that rat-ridden tenements breed endemic typhus, that mosquito-breeding pools near unscreened dwellings cause malaria; that insanitary privies, unlighted, shared toilets, polluted wells, and connections between sewerage and water supply systems promote intestinal disease; that room-overcrowding facilitates the transmission of diphtheria and scarlet fever and meningitis and penumonia?
>
> There are some 30,000 fatal accidents which occur each year in the home—nearly as many as are attributable to the automobile. Can it be doubted that rickety steps and rotten handrails, dark stairways, wood stoves, and kerosene lamps contribute to a substantial proportion of these fatalities?
>
> Health, however, means more than just staying alive. Health means vigor and efficiency and satisfaction in living. The primary purpose of the home is shelter against the elements and the provision of an inner environment in which man can function to better advantage. The shack which has no heat in winter and the tenement which has no cross-ventilation in summer are not compatible with health. Nor is the dwelling with no sunlight by day and no adequate illumination by night. Nor the dwelling where elevated railroads or automobile horns shatter the repose of the sleeping hours.
>
> Finally, we must take into account the demands of emotional as well as of physiological health. The home is a work place where some sixty hours of labor must be performed on the average every week. If conditions are not such as to facilitate performance of the household tasks, fatigue results, as surely as in any factory workroom. Some opportunity for privacy—"a room of one's own" or its nearest possible equivalent—is an essential need for emotional health; and on the other hand, opportunities for normal exercise of the social functions is equally necessary. The Committee on the Hygiene of Housing has correctly pointed out that more damage is done to the health of the children of the United States by a sense of chronic inferiority due to the consciousness of living in substandard dwellings than by all the defective plumbing which those dwellings may contain.
>
> Bad housing, as a matter of practical fact, is profoundly detrimental to

health; and the existence of the slum is a health problem of outstanding significance.

BASIC PRINCIPLES

The 30 specific characteristics of housing referred to in the foregoing were presented in detail in an earlier report (reprinted as an appendix in *Housing for Health**), together with suggested means of attainment. They are believed to represent "fundamental minima required for the promotion of the physical, mental, and social health, essential in low-rent as well as in high-cost housing, on the farm as well as in the city dwelling." They deal with housing management as well as planning and construction; they represent the well-considered conclusions of a group of specialists based upon some years of study, observation, and research.

Briefly summarized, these *Basic Principles* cover the following matters.

PHYSIOLOGICAL NEEDS. The thermal environment must be such as to avoid undue heat loss and to permit adequate heat loss from the human body. Air must be of reasonable chemical purity as regards odors, smoke, fumes, and soot from within or without the house. There should be suitable natural light, including some sunlight, adequate artificial lighting, freedom from excessive noise, and space for exercise and play.

PSYCHOLOGICAL NEEDS. There should be provision for individual privacy and for the sociability of normal family life and of community life. Means should be available for the performance of household labor without undue physical and mental fatigue, and for maintenance of personal and household cleanliness. The home and its surroundings should provide for aesthetic satisfaction and be in concord with the prevailing social standards of the local community.

PROTECTION AGAINST CONTAGION. A water supply of safe sanitary quality protected against pollution within the building, toilet facilities that will minimize the danger of transmitting disease, and a properly designed and installed plumbing system are first essentials. Unsanitary conditions in the vicinity and vermin are to be avoided. Refrigeration for food and ample sleeping space to minimize the danger of contact infection should be provided.

PROTECTION AGAINST ACCIDENTS. Under this classification are

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* *Basic Principles of Healthful Housing*, 2d ed., American Public Health Association, committee on the hygiene of housing, 1939.

included structural safety of the building itself, elimination of fire hazards, provision for escape in case of fire, protection against electric shock and burns, against accidental falls in the home and against the hazards of automobile traffic.

This report deserves careful study by anyone whose major interests lie in the direction of housing. Many of the principles outlined are discussed at greater length in the chapters which follow.

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CHAPTER 3

THE AIR SUPPLY OF ENCLOSED PLACES

THE PROBLEMS OF VENTILATION

Within any enclosed space where people are living and working, there exists a modified air environment having two outstanding characteristics. The temperature, humidity, and other physical conditions are under control and, within wide limits, may be modified at will; and the air is subject to pollution by human occupants and, at times, by industrial operations. It may happen, too, that the industrial or manufacturing operations, although not necessarily producing undesirable changes in the air, yet have certain requirements as to temperature or humidity which bear upon the health of the worker. This was long the situation in the textile industry, where the operations of spinning and weaving were best conducted under conditions of excessively high humidity. In other situations, as in deep mines, unhealthful conditions exist as a result of the physical surroundings.

Measures adopted for the control of the air supply must, in the first instance, be related to the specific conditions to be maintained, prevented, or remedied. Thus, whereas the terms *ventilation* or *air conditioning* are frequently employed in a broad way to cover remedial or corrective treatments in general, more detailed study of particular situations will disclose specific needs and indicate one or another type of control. In brief, diagnosis properly precedes treatment. The problems of ventilation are in fact largely problems of diagnosis, which, in turn, involve the study of human requirements and tolerances and the establishment of standards of permissible departures from the optimum air conditions.

We proceed, then, to somewhat detailed consideration of the effects of human occupancy and of the various industrial operations upon the air of enclosed and occupied places, particularly as these effects may be related to the health, comfort, or efficiency of the occupants. But, as these two types of pollution, from human occupancy alone and from industrial operations, differ greatly as to causes, effects, and treatments, they are best dealt with separately and as wholly independent problems.

AIR POLLUTION BY HUMAN OCCUPANCY

Early Views. The "vitiation" of the air of an enclosed space by human occupants attracted the attention of physiologists at an early date. The analogy of suffocation of a mouse or extinction of a lighted candle under a bell jar, may have led to a belief that lack of ventilation of crowded rooms and subsequent discomfort was similarly a matter of depleted oxygen, but this view never received scientific support. Lavoisier (1770), who gave us the first scientific knowledge of the chemistry of respiration, concluded that the ill effects of lack of ventilation were due to the accumulation of the by-product of combustion, which we now know as carbon dioxide, rather than to the lowering of the oxygen content of the air.

Nearly a century later Pettenkofer* expressed the belief that, under the conditions of normal habitation, the carbon dioxide content of the air never reaches a level at which it begins to manifest harmful symptoms, as indicated by laboratory tests. We may note, for example, (Table 1) the conditions as relating fresh air, the air within the lungs (respired air), and the air of certain places. Nevertheless, the carbon dioxide theory has persisted almost to our own day, as witness various codes and ventilation standards of recent years.

The facts are that in the worst-ventilated and crowded rooms the oxygen content may fall from 21 to 20 per cent, and the carbon dioxide rise to one half of one per cent. These values are quite without physiological significance. The air of the lungs normally contains 16 per cent of oxygen and 4 per cent of carbon dioxide. This condition is automatically maintained by modification of the depth and frequency of breathing and is almost uninfluenced by any considerable range of outside air conditions. Only when the carbon dioxide in the air reaches a concentration of about 5 per cent is there any distress except during vigorous exercise, when a somewhat lower concentration begins to be felt.

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* Max Joseph Von Pettenkofer (1818–1901) the Bavarian chemist and hygienist, might truly be called one of the early public health engineers. The unhealthy living conditions in Munich, about 1850, drew his attention and interests from studies in theoretical chemistry to matters of practical hygiene, fresh air, pure water, and adequate sewage disposal.

TABLE 1

COMPOSITION AND TEMPERATURE OF NORMAL AND OF RESPIRED AIR AND OF THE AIR OF CERTAIN PLACES

	Normal	Respired	Poorly Ventilated Crowded Room	Mine*	Brewery	Pike's† Peak
Oxygen	21%	16%	20%	17%	..	13%
Carbon dioxide	0.04%	4%	4%	..	1 to 2%	..
Aqueous vapor	1.2%‡	6%	4%	..	..	..
Temperature centigrade	20°	35°	..	..	..	..

* Maintained at low partial pressure to minimize danger of explosion.

† Partial pressure of oxygen referred to normal air at sea level.

‡ At relative humidity of 50 per cent.

Various hypotheses have also been advanced as to specific toxic substances in the exhaled breath, but all have failed of satisfactory experimental demonstration. Thus physiologists eventually turned their thoughts from chemical vitiation to other observed changes, especially to the physical changes in the thermal properties of the air, regarded now as a cooling agent. Two items that affect the physical property of cooling have been included in Table 1, moisture and temperature.

THE MODERN VIEW. The influence of the temperature and humidity of the surrounding air upon comfort had been noted from time to time and occasionally emphasized as the principal cause of discomfort, but it remained for Flugge and his colleagues, in 1905, to present the data necessary to establish what is now held to be the correct basis of ventilation theory. From a long series of their experiments, carried out under various conditions, the following one is selected as typical and convincing.

A subject was shut up in a small cabinet without ventilation. When the temperature of the air had risen to 30.2 degrees centigrade, its relative humidity to 87 per cent, and its carbon dioxide content to 1.1 per cent, the subject became very uncomfortable. He experienced no relief upon being allowed to breathe the outside air through a respirator, but was immediately relieved when the air within was cooled to 17 degrees centigrade by circulating cooling water in pipes, although the carbon dioxide had by that time risen to 1.6 per cent. In similar experiments, subjects outside the cabinet felt no discomfort while breathing the air from within through respirators.

Since that time numerous and extensive investigations have been made of these matters in many parts of the world and under many experimental conditions. They have all pointed to the same conclusion, one which was so well and so tersely stated by Professor Frederick S. Lee of the New York State Commission on Ventilation: *The problems of ventilation are physical, not chemical; cutaneous, not respiratory.*

In brief, the human body is an engine which converts fuel into work, and wastes heat in the process, as must be the case in any thermal engine. Like the engines of our automobiles, the body has its circulating cooling fluid and its radiator surface. Its effective cooling depends upon the physical transfer of heat to the surrounding atmosphere and upon suitable internal arrangements to regulate this transfer. Therefore, any definition of most favorable air conditions—and this is the objective of our studies—must be based, in part, upon a proper understanding of the physical laws of heat transfer and the physiology of body cooling.

These subjects are dealt with in detail in the following chapter. For the present it will be useful to consider a distinctly different type of atmospheric pollution due to human occupancy—bacterial pollution—and finally some of the more important kinds of pollution that may be associated with industrial processes.

AIR BACTERIOLOGY

It has been seen how the attention of the early physiologists and hygienists was directed first to the chemical vitiation of the air and later to its physical properties as a cooling mechanism. The current revival of the theories of air-borne infection must be dealt with in a new set of terms, in terms of bacterial flotation and survival in the air, and of the epidemiology of diseases, particularly as regards modes of infection.

An Ancient Doctrine. The possible relation of the air to disease transmission is not a new thought. In 1546 Fracastorius wrote:

> For along with the air that is drawn in, there enter, mixed with it, germs* of contagions, and when once these have been introduced, they do not retire as easily by expiration as they entered by inspiration; for they adhere closely to the humors and organs, and some even to the

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* In the original *seminaria* which the translator distinguishes from *semina*—seeds—as having the significance of *seed beds.*

> spirits, which retreat from the image of their contrary, and carry their enemy with them, even to the heart. For we must not say, as some do, that poisons and contagions try above all to make for and attack the heart, like an enemy, as though they possessed cognition and will.*

and,

> Now of these contagions which come from without, the air is the most potent cause, though they may also come from water, marshes and other sources. The air is the most suitable medium, partly because it very easily received both its own and foreign infections, and because we have to use it to live. And we must not fail to observe that the air is sometimes merely modified by becoming heated, or cooled, or drenched, or dried, but sometimes it not only alters thus, but also transmits to our bodies foreign vapors, which are themselves not "simple," but are also germs of contagions. Now the difference between a simple vapor and the germ of a contagion is that a vapor is a highly alterable thing made of a combination which is not strong and viscous, such as that of which the germ is made. Germs . . . procreate other germs precisely similar to themselves, as progeny, which, when carried to another object, transmit the contagion to it.†

TRANSMISSION BY CONTACT. This frankly expressed belief in the aereal transmission of disease extended back at least to the time of Hippocrates (400 B.C.) and was firmly held well into the 19th century. But, when the studies of Budd, of Snow, and of the early bacteriologists established the facts concerning the water-borne and food-borne nature of some of the intestinal infections, and even *malaria*—the classic disease of *bad air*—was found to be mosquito-borne, belief in air-borne infection yielded to scepticism and finally to frank agnosticism among the philosophers of medicine.

Pasteur gave to the world the scientific proof that air carries floating germs, and it is fundamental folklore that foodstuffs can be preserved by canning and heating, but rapidly spoil when again exposed to the air. Yet the *infectious diseases* were now presumed to be conveyed from victim to victim by actual *physical contact* or, at most, by secondary contact with contaminated clothing, water, or food; or by air contact within the radius of influence of droplets expelled when speaking, coughing, or sneezing; or by air-borne insects, but in no other way air-borne.

RENAISSANCE OF THE AIR-BORNE HYPOTHESIS. This extreme position was eventually found to be untenable, and early in the present century a few investigators, notably Trillat in France, were study-

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* Fracastorius, *De Contagione*, translated by W. C. Wright, New York, 1930, p. 35.

† *Ibid.*, p. 57.

ing, by modern scientific methods, the possibilities of air-borne infection, especially infections of the respiratory tract which, logically enough, might be presumed to enter the body by means of the respiratory air.

It is largely due to Wells* that a complete hypothesis of air-borne infection, supported by laboratory and other experimental evidence, was brought to the attention of the medical world and has since been widely accepted. Wells expanded the theory of droplet infection to show that, whereas droplets of large size do, in fact, fall to the floor within a short distance of their point of production, droplets of smaller size—and in far greater numbers—are evaporated rapidly and left floating in the air as suspended *nuclei,* consisting only of a solid residue left by the evaporation of the saliva and its associated bacteria.

These nuclei are in a state of suspension somewhat comparable to that of tobacco smoke, and are capable of remaining suspended for a matter of hours or even days, and of drifting about wherever supporting air currents may carry them. An excellent criterion of the carrying capacity of drifting air is the corresponding rapid drift of odors, say of the kitchen or of tobacco smoke, up- and downstairs, and through the various rooms of a home. Air, in fact, is seldom quiescent. The slightest mechanical movement sets it in motion, and it is highly susceptible to temperature differentials. During the heating season especially, cold air continuously descends along the outer walls of the room and down the lower portions of stairways and through the lower halves of doorways, while warmer air moves as steadily in the opposite directions. The total effect is a rapid transfer of any air-borne substances throughout any set of connected rooms.

The concept of bacteria-bearing nuclei, capable of long-time flotation in the air, is therefore one of great significance. Even after these nuclei have settled to the floor of the room, they have not wholly lost their importance. There is abundant evidence that resuspended dust particles may constitute an important and, under certain circumstances, the most important part of the air pollution.

Wells's further contributions to this hypothesis were, first, a machine for the quantitative bacteriological examination of air

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* W. F. Wells, *Am. J. Pub. Health,* **23**, 58, 1933; *Am. J. Hyg.,* **20**, 611, 1934. W. F. Wells and W. R. Stone, *Am. J. Hyg.,* **20**, 619, 1934. W. F. Wells and M. W. Wells, *J. Am. Med. Assoc.,* **107**, 1698, 1805, 1936.

and, second, the demonstration in the air of occupied places of numerous bacteria, but especially of a typical organism (an alpha hemolytic streptococcus) which is a characteristic inhabitant of the normal nose and throat.

Just as the quantitative presence of the characteristic intestinal organism, *E. coli* in a domestic water supply is an accepted measure of the extent of pollution of that water by excreta (see chapter 10) so the characteristic streptococcus of the nose and throat may be regarded as a measure of atmospheric pollution by bacteria-laden nuclei of human origin.

Buchbinder, in a critical review of the data and of current thought, has well summarized the situation (as of 1942). Referring to the work of Trillat, Wells, and others, and to his own extensive studies, he says:

> A synthesis of their findings and those of others gives us a hypothesis which, while it does not invalidate the droplet idea *per se,* brings into question its relative significance. Stated simply, the indirect or air-borne hypothesis postulates that the greatest spread of respiratory infection is produced by small dried droplets floating in air for relatively long times and distances, or by the resuspension of dried droplets in air after they have settled to surfaces such as floors, clothing and bedclothes. This hypothesis has been advanced by three lines of investigation.
>
> . . . The first consists of evidence adduced by surveys and laboratory studies. It has been shown that an organism such as the alpha hemolytic streptococcus, which is a common nonpathogenic inhabitant of the upper respiratory tract of man, can be recovered readily from man's environment. This organism can survive for days in indoor environments, and the numbers found in any location seem to serve as an index of the conditions of occupancy and ventilation. Strains of the human pathogenic, group *A,* beta hemolytic streptococcus can also be recovered from a "normal" environment with practically unimpaired virulence, although in relatively small numbers. In the laboratory it has been shown that streptococci artificially sneezed into air float for relatively long periods. They settle out geometrically, and, having settled, they die geometrically at rates which vary with the length of the bacterial chain and prevailing conditions of the environment. Organisms which have settled out of air may be readily resuspended therein. In the presence of sunlight and even diffuse daylight which have passed through the glass of a window, both streptococci and pneumococci on a simulated floor die at a much faster rate than they do in the dark. If the air-borne route is an important vehicle for the spread of respiratory infection, then ordinary diffuse daylight in rooms may act as a strong deterrent to the spread of such infections.

Little is known of the manner of spread of virus infections of the respiratory tract, but it has been shown in the laboratory that ferrets can be infected by spraying the air with influenza virus, and that this virus can be recovered from the air after thirty minutes. Likewise, when the intact chorioallantoic membrane of the developing chick embryo is exposed to air sprayed with vaccinia virus, the virus can be recovered for at least eight hours.

Investigations of hospital infections, particularly those occurring in contagious disease hospitals, have furnished a second group of data supporting the air-borne hypothesis. It is now apparent that such infections constitute a serious problem in these institutions as well as in children's, maternity and other hospitals. A long time ago the contact theory seemed to have been confirmed by the success of the so-called barrier method of nursing in contagious disease hospitals, and so it is curious that the best clinical evidence for the air-borne hypotheses has now been furnished by institutions of the same kind. In isolation hospitals, particularly where cross infections due to streptococci and diphtheria bacilli are most prevalent, organisms similar to the causative ones are now known to be present in the air in relatively large numbers, and may be presumed to be of practically undiminished virulence. On the whole the data furnished by recent studies on the spread of hospital infections are most satisfactorily explained by the air-borne hypothesis.

The third line of evidence has been given by what might be called a therapeutic test of the air-borne hypothesis. Measures designed to rid institutional environments of pathogenic micro-organisms should also reduce the incidence of new infections therein. Sufficient laboratory evidence now exists to indicate that ultraviolet light and chemical sprays, the so-called aerosols, may serve as powerful bactericides. The few reports on clinical trials thus far available contain suggestive evidence that in children's hospitals and operating rooms the use of ultraviolet light reduces the incidence of new infections. Furthermore, several reports indicate that the spread of chickenpox in institutions is inhibited by this means.

THE EFFECTS OF INDUSTRIAL OPERATIONS

Many of the activities of industrial plants bring about significant changes in the environment, in addition to those resulting directly from human occupancy. These industrial conditions are so varied both qualitatively and quantitatively and call for such specialized treatment that it is difficult to undertake even a generalized classification. Some of the major groups of effects however may be listed and defined.

Temperature and Humidity. Among the industrial conditions, both high and low temperatures are frequently encountered. High temperatures are quite common. Workers in steel-rolling mills and in boiler rooms are exposed to intense radiation, in addition to a high air temperature. This is hot dry air. Large quantities of water are drunk, and *heat cramps* may result from the loss of salt through the sweat and consequent reduction of the osmotic pressure of the body fluids. This condition is remedied by the administration of salt.

Laundry workers are exposed to a hot moist air, a particularly unfavorable combination. Similar conditions prevail in the dye houses of textile mills. High humidity at ordinary temperature is frequently observed. This results in damp clothing and body chilling when the worker goes out into a cold air.

In cold-storage rooms, the aging rooms of breweries, and similar places, low temperatures are maintained. These conditions are more readily offset by suitable clothing, but workmen passing in and out are subject to the unfavorable effects of sudden changes. Physical labor in the saturated cold air of an icehouse causes profuse sweating, which saturates the clothing and largely reduces its insulating property.

Other characteristics of industrial conditions are the various air contaminants that are associated with many operations. These may be classified, according to their physical state and origins into dusts, fumes, smokes, mists and fogs, vapors and gases.

DUSTS are particulate matter in a temporary state of suspension, due to their high degree of dispersion. Those particles capable of being inhaled range in size between 0.5 and 10 microns. As a group they cause mechanical irritation in the upper respiratory tract and may accumulate in the lungs. Soft-coal miners often show, on autopsy, completely blackened lungs.

Dusts may be chemically irritant, toxic, or abrasive. Organic dusts may excite allergic reactions; they may consist of bacteria, the spores of fungi, or other living material.*

Dusts containing silica (SiO_2), if breathed in quantity or over a period of years, produce a pathologic condition of the lungs known as *silicosis*. Silica dusts are associated with hard-rock mining, quarrying, tunneling, and stone working. They are found in the air of foundries, from the use of molding sand, and in wood-working establishments, resulting from the operation of *sanding*.

Asbestos, a magnesium silicate, is extensively mined and worked into fireproofing materials and fabrics. Its inhalation leads to another lung disease, *asbestosis*. Other silicate dusts appear to lack the peculiarly harmful effects of asbestos and of silica.

FUMES. As employed in industrial hygiene the term *fumes* refers, rather indefinitely, to metallic and metallic-oxide dusts, in an exceed-

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* R. R. Sayers, *U. S. Pub. Health Service, Pub. Health Repts.*, 53, 217, 1938.

ingly fine state of suspension, as they arise from the molten metal. Fumes may also arise from other volatile substances. They are considered to be colloidal dispersions of solid materials.

MISTS AND FOGS. These differ from fumes in that they are condensed to a finely divided liquid form or have resulted from atomizing a liquid. The terms are familiar to us when water is the dispersed system.

VAPORS AND GASES. These terms have their usual connotation. We speak of the vapor of benzol, a volatile liquid at ordinary temperature, and of carbon monoxide gas, normally gaseous.

SMOKE is a colloidal system of the products of incomplete combustion. It is characterized by its optical density. It is usually accompanied by other products, irritating to the eyes, throat, and lungs; the highly toxic carbon monoxide is also likely to be found in the smoky products of incomplete combustion.

OTHER CLASSIFICATIONS. The various atmospheric impurities may be further classified, according to their effects, as irritants, or toxic, infectious, or allergic agents, or as associated with certain specific pathological effects. They are also distinguished as to the portal of entry. The three principal portals are the respiratory tract, through inhalation; the stomach, through swallowing; and the skin, through direct absorption.

PHYSIOLOGICAL STUDIES. Fortunately, for our present needs, it will be unnecessary to list either the many industrial processes involved or the specific air contaminants of each. Among the organic solvents alone, the number of different compounds employed is very large and is constantly growing. Each such material must be studied with reference to its physiological reactions when breathed or brought into contact with the skin.

This is the work of the physiologist, and a large amount of information has been gathered and tabulated concerning the specific effects and the limits of tolerance of many of the commoner substances. The better of these studies report tolerance as a time-of-exposure function; that is, a given concentration in the air may be tolerated for a stated period, in hours per day or per week, or perhaps, as in the case of silica dust in stone working, in total years of exposure.

It is unfortunate that the development of new industrial processes and the rapid introduction of new chemical substances has gone far ahead of this logical program of health protection. It too often happens that the first experiments are made upon the worker and that an investigation of tolerance is undertaken only after illness and the threat of serious compensation claims draw attention to the unhappy results of some new process or new air contaminant.

Adaptation. Workmen in industry appear to be subject to a considerable degree of adaptation whereby they accustom themselves to conditions that seem almost intolerable to the casual visitor. This is not only true of high temperature and humidity, but also noticeably true of irritating gases such as sulphur dioxide. This tolerance is not necessarily an actual immunity, nor does it preclude the possibility of delayed unfavorable reactions. Such matters are deserving of thorough investigation before being accepted as unavoidable conditions of the "job," unpleasant perhaps but harmless because tolerated.

The functions of industrial hygiene, as related to atmospheric conditions, are to mitigate, as far as practicable, the unfavorable conditions of industrial employment and to eliminate excessive hazards. Suitable investigation, based upon adequate physiological and pathological studies, will usually suggest the substitution of some new and less objectionable materials, such a new solvent in place of benzole; improved equipment for handling dangerous substances; more adequate and perhaps specialized ventilation; or, at times, the shortening of the hours per day or days per month of unavoidable but dangerous exposure.

MEASUREMENT OF ROOM AND AIR CONDITIONS

The physical characteristics of the air of rooms commonly measured and recorded are temperature, humidity, and movement. The mean radiant temperature of the surrounding walls has also come to have considerable significance in modern views of body cooling, and in industrial hygiene interest often centers in the amount and nature of suspended or gaseous impurities. To these measures of single properties must be added several procedures for the measurement of multiple properties, with the object of evaluating in one item the *cooling power* of the air with respect to the human body.

TEMPERATURE

Thermometers. Air temperature is measured by an ordinary thermometer. It must be appreciated, however, that the thermometer responds also to radiant heat as evidenced by the familiar expression, "90 degrees in the shade." The corresponding temperature in the sun might be 20 degrees higher. In any place like a boiler room, exposure of the thermometer to high-temperature radiation is to be avoided by proper "shading."

The *black-bulb thermometer,* as employed by the Weather Bureau, is designed to absorb a maximum proportion of the incident radiant energy, and, exposed directly to the sun, gives an indication of the intensity of the solar radiation. The *silvered thermometer* has the opposite purpose of reflecting as much of the incident radiation as possible and thus of giving a truer reading of air temperature.

ELECTRICAL METHODS. There are two devices for the measurement of temperature by its effect upon electrical properties. These have the advantage of permitting temperature measurements to be made in inaccessible places and at a distance.

The *thermoelectric couple* is one of these. Its operation depends upon the fact that, when two dissimilar metals are brought into contact, Figure 1*A,* there is a movement of electrons from one to the other by virtue of which a difference of potential, the contact electromotive force, is established. The value of this potential is a specific property of each metal, as against each other metal, and of the temperature. If the circuit be completed, Figure 1*B,* the potential differences at the two junctions are equal and opposite, unless these junctions are at different temperatures when a current is established, which can be measured in a galvanometer.

The relation between current and temperature difference is essentially linear, and after the system has been calibrated against a few known temperature differences it serves to measure the difference between any unknown temperature at the *hot junction* and the known temperature at which the *cold junction* is maintained.

Commercial apparatus substitutes another electrical arrangement for the cold junction, and its galvanometer reads directly in temperature degrees. A homemade apparatus is readily constructed by the use of iron and constantan wires and a suitable galvanometer, or preferably a potentiometer. This system has an electromotive force of about 40 microvolts per degree centigrade which can be increased by the employment of multiple junctions in series, Figure 1*C.*

The resistance thermometer is another convenient apparatus for the measurement of temperature at a distance. The electrical resistivity of most metals and alloys increases with increasing temperature. The resistivity of soft iron, for example, increases by about 0.6 per cent per degree centigrade of temperature increase. On the other hand, manganin, an alloy of copper, manganese, and nickel, shows almost no change in resistivity with temperature. A combination of two resistance coils, one of iron and one of manganin, arranged as two arms of a Wheatstone bridge, provides a means of measuring the temperature to which the coils are exposed, Figure 1*D*. This is the basis of the instrument devised by Whipple, the *thermophone,* for the measurement of the temperature of lakes at any desired depth.

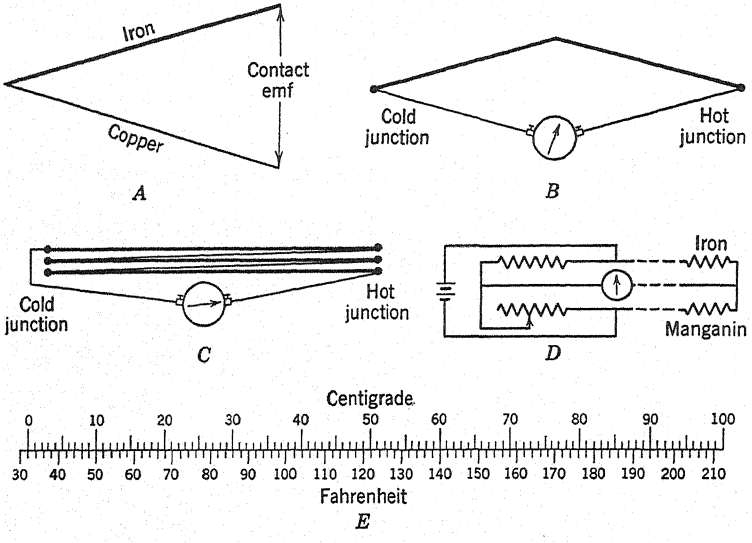

Fig. 1. *A, B* Principle of the thermoelectric couple.
C A multiple-junction couple.
D Electric circuit of the resistance thermometer.
E Temperature conversion scale.

These electrical devices have the further advantage of being readily connected to recording apparatus to provide a continuous printed record of the temperature.

Radiation. Surrounding walls, floor, and ceiling radiate heat to the interior. This radiant energy can be measured directly, and for any limited area of wall by the usual methods of radiometry. This is a laborious process and calls for the integration of radiant intensity over the entire subtended sphere.

The *mean radiant temperature* is measured approximately, along with certain other physical properties of the air, by certain special devices which are referred to in a later section (p. 50).

HUMIDITY

Humidity, the moisture content of the air, may be expressed in terms of actual volumetric concentration, per cent by volume, of aqueous vapor, or as *relative humidity* or *per cent saturation*. The first method is illustrated in Table 2 in which the aqueous vapor is treated as one of the gaseous components of the air. The second, relative humidity, is more commonly employed, because it indicates that property of the air in which our interest centers, its capacity to evaporate water. It refers to a physical property of water, its vapor pressure, the meaning of which it is desirable to understand in order to appreciate the significance of relative humidity.

PRESSURE OF AQUEOUS VAPOR. Water tends to evaporate into any space to which its surface is exposed. If that space is enclosed, the concentration of aqueous vapor builds up, as does the rate of return of water molecules to the liquid phase by collision at the surface. Eventually a point is reached at which the rate of return just equals and counterbalances the rate of escape. At this equilibrium condition, evaporation may be thought of as continuing at its own rate, but net effective evaporation ceases, and the partial pressure of the aqueous vapor in the space above is the *vapor pressure* of the water. This varies with the water temperature, as is illustrated in Table 2.

TABLE 2

TEMPERATURE AND VAPOR PRESSURE OF WATER

Temperature, °C	Vapor Pressure	
	mm of Hg.	Percent of Atmosphere
0	4.6	0.06
20	17.6	2.32
40	55.4	7.30
60	149.4	19.7
80	355.0	46.7
100	760.0	100.0

The last column indicates the relative pressure of the vapor in air at normal atmospheric pressure, and hence (somewhat imperfectly) the concentration of the vapor in the air expressed as volume per cent. It is more correct however to regard the pressure of the aqueous vapor as existing alone, as it would if the space were originally a total vacuum. Its value depends only upon the water temperature and is independent of the presence or absence of any other gases within the space or of the amount or pressure of such other gases. Of the total gas pressure at equilibrium, the aqueous vapor constitutes that part represented by the vapor pressure of water as defined.

RELATIVE HUMIDITY. Under this condition of equilibrium between a free water surface and the space above, the air (more properly the space) is said to be *saturated.* A condition of supersaturation is unstable and does not ordinarily exist. Conditions of undersaturation however do exist. In the presence of free water they are unstable and move toward saturation, but normally air carries with it less aqueous vapor than sufficient to saturate the space.

Relative humidity is a measure of the concentration of aqueous vapor in the air expressed as a percentage of the saturation value. At 100 per cent relative humidity air will not evaporate water. If such air is warmed, its absolute humidity is not altered, but its relative humidity is lowered. In Table 2 the saturation value at 0 degrees has a partial pressure of 4.6 millimeters of mercury in a total atmospheric pressure of 760 millimeters. If this same air be warmed to 20 degrees, *out of contact with water,* its relative humidity will be changed from 100 per cent to 4.6/17.6 or 26.1 per cent, a relatively dry air. This point will be found to be of considerable practical interest in some of our later discussions.

PSYCHROMETRY. The measurement of relative humidity is best done with the aid of the *wet- and dry-bulb thermometer* or *sling psychrometer.* If a thermometer, having its bulb covered with a thin wet cloth, be moved rapidly through the air, as by being whirled about in a small circle, it will be cooled a few degrees and come to a condition of equilibrium at which further whirling does not bring about any further lowering of temperature. This temperature is the *wet-bulb temperature* of the air, and its departure from the *dry-bulb* or normal air temperature is the *depression of the wet bulb.*

Obviously, if the air is saturated there will be no evaporation and no cooling. A zero depression then represents 100 per cent of saturation. The dryer the air, the more the evaporation and the greater the depression. With this type of reasoning and on the basis of a large number of experimental determinations, an empirical formula has been developed by the U. S. Weather Bureau from which its well-known Psychrometric Tables have been computed.

Later studies by Carrier have demonstrated that the wet-bulb temperature is actually the temperature to which any given air will be cooled by its adiabatic saturation: that is, if it be allowed to evaporate sufficient water to saturate itself, all the heat required for the evaporation being abstracted from the air.* This analysis, and subsequent experimental confirmation, produced a rational formula and the psychrometric chart.†

A modified psychrometric chart, drawn from the data of the Weather Bureau tables, is reproduced in Figure 2. It is sufficiently accurate for all practical purposes of air examination.

Psychrometers in which a wet-bulb thermometer is exposed to still air are quite unreliable, although they are sold in considerable numbers and are frequently seen on office walls, generally with the water reservoir empty. Placed in the strong breeze of an electric fan these instruments give readings fairly close to the true wet-bulb temperature. Other types of psychrometer depend upon the change in length of a hair or other hygroscopic substance. They are unreliable in ordinary use, although, employed, with proper calibration, in meteorologic balloons and elsewhere, they have certain advantages and usefulness.

The *dew point* of the air is the temperature to which the air must be cooled before it becomes saturated with moisture. It is determined by causing a stream of air to pass slowly over a polished metal plate, the temperature of which is very slowly lowered until a slight condensation of moisture appears. The temperature is then noted. Since the air is saturated at its dew point, reference to a table of saturation values gives the actual humidity, and this divided by the saturation value at the initial air temperature gives the relative humidity. The psychrometric tables also give the dew-point values as related to the wet- and dry-bulb readings.

Table 3 is a short table of dew points, as related to temperature and relative humidity, for use in approximate estimates of air conditions. The temperatures of the dew point are accurate to the nearest degree.

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* W. H. Carrier, *Trans. ASME,* **33,** 1005, 1911.

† See *Guide Am. Soc. Heating Ventilating Engrs.*

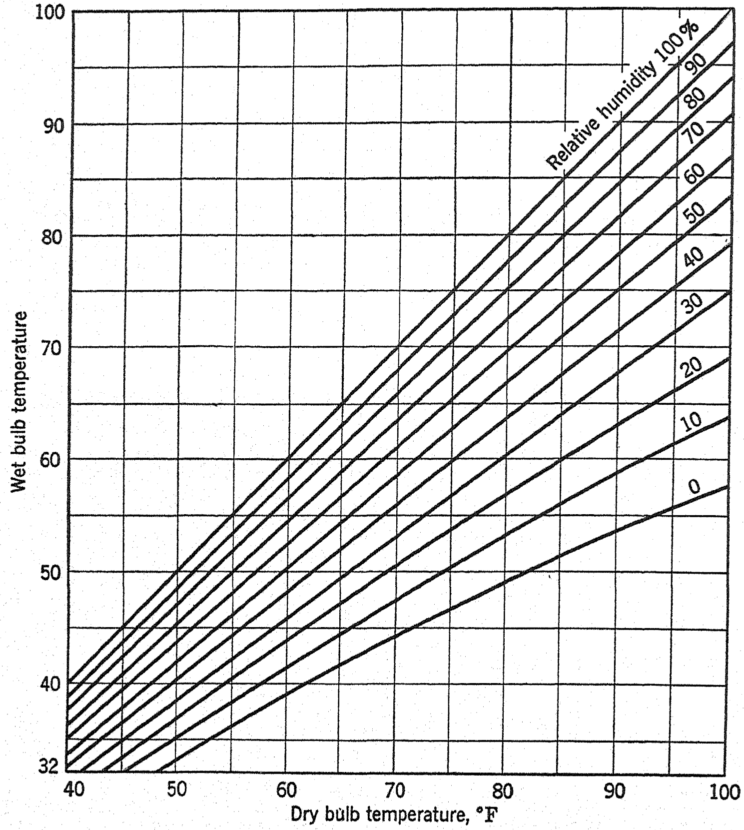

Fig. 2. Psychrometric chart.

TABLE 3

A Short Table of Dew Points—Fahrenheit Scales

Air Temperature	Relative Humidity, Per Cent								
	10	20	30	40	50	60	70	80	90
	Dew Points								
40	..	3	12	18	23	27	31	34	37
50	..	11	20	26	31	36	40	44	47
60	4	18	27	34	40	45	50	54	57
70	11	25	35	43	49	55	59	63	66
80	17	33	44	52	59	64	69	73	77
90	24	41	52	61	68	73	78	83	87
100	31	49	61	70	77	83	88	92	96

AIR MOVEMENT

The amount of movement of the air is an important characteristic of room conditions. It is also necessary at times to measure air velocities in ventilation ducts in order to compute air volumes available for ventilation.

THE STANDARD ANEMOMETER. The anemometer is merely a windmill of special design. One form is employed by the Weather Bureau in the measurement of wind velocities. It is calibrated so that its revolutions per minute or per hour, which are automatically counted, can be translated into feet per minute, miles per hour or other convenient measure of velocity.

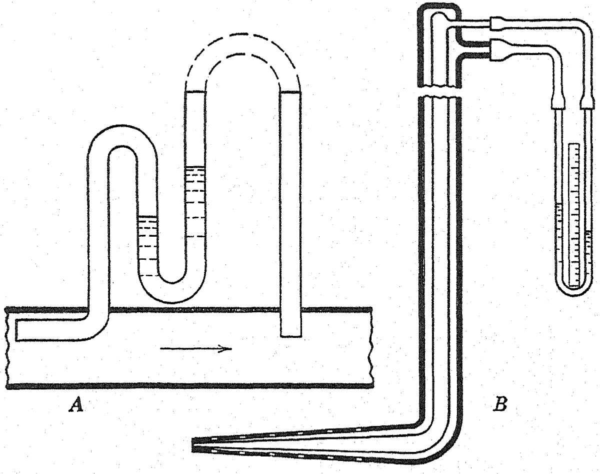

FIG. 3. The Pitot tube.

THE PITOT TUBE. This is a more fundamental instrument in that the interpretation of its readings is based upon dynamic theory. Instruments like the anemometer are always calibrated against some such instrument as the Pitot tube.

Figure 3*A* illustrates the principle of its action. Air, moving as indicated, strikes the open end of the tube which it enters to a slight extent, until the pressure within the tube, indicated on the manometer, is exactly equivalent to the force of impact of the moving air as it is brought to rest. The relation between the energy of movement of a fluid and pressure is derivable directly from the laws of falling bodies. Expressed in units commonly employed in dealing with air velocities, and for air at 70 degrees Fahrenheit, the relation is

$$V = 4000\sqrt{h}$$

in which V is the air velocity, in feet per minute, and h the pressure indicated in the manometer, in inches of water. Thus an air current having a velocity of 1000 feet per minute will support a water column 1/16 of an inch in height. This pressure equivalent of the air velocity is the *dynamic pressure* of the system.

The air within the duct, being in motion, is usually under pressure in the usual sense of the word, that is, *static pressure*. This pressure, unlike the dynamic pressure, reacts equally in all directions and is included in the total pressure recorded by the Pitot tube facing the stream flow. A similar tube, with opening parallel to the flow, will record the static pressure but will be unaffected by the dynamic pressure. By connecting two such tubes, as indicated in the figure, the static pressure in the system is automatically subtracted, and the resultant manometer reading is due wholly to the pressure of motion of the air.

In practice a Pitot tube has the appearance shown in Figure 3*B*. The long slender nose has a small opening at its end which is brought to face the air stream. This communicates with one manometer connection. The nose is also jacketed, and the jacket is pierced with many very small holes, parallel to the stream (as it is slightly diverted by the instrument). The jacket communicates with the other manometer connection. The instrument is inserted through a small opening in the side of any duct and rotated slightly until the maximum reading is observed, thus assuring correct presentation of the end opening to the air stream.

THE HOT-WIRE ANEMOMETER. The rate of cooling of a heated object is related, among other things, to the velocity of air movement. This principle is employed in various modifications of the hot-wire anemometer. Some of these are of particular usefulness in measuring very low velocities, such as occur in the ordinary room. A convenient device* consists of an ordinary thermometer, around the bulb of which is wound a coil of resistance wire. This forms part of an electric circuit in which the current can be controlled and the voltage across the resistance wire read. The voltage required to main-

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* C. P. Yaglou, *J. Ind. Hyg. Toxicol.*, **20**, 497, 1938. Made by Wilson Products Inc., Reading, Pa.

tain the temperature of the thermometer at a fixed predetermined point depends upon the air temperature and the velocity of its movement. Calibration charts are furnished with the instrument.

The *Kata thermometer* (p. 49) also measures air movement as one element of the cooling value of the air. It has been calibrated for use as an anemometer and is quite sensitive to slight air movement. The formula and calibration are furnished with the instrument.

The *Velometer,** another useful instrument for indoor measurements, has a delicately balanced vane against which the air current impinges and which is deflected according to the air velocity. It has a calibrated scale.

SUSPENDED AND VOLATILE IMPURITIES

The hygienic significance of many of the air contaminants associated with various industrial activities has led to the development of laboratory procedures for the examination of air for these impurities. Within recent years the possibilities of air-borne disease and of the travel of pathogenic bacteria through the air have become more definitely appreciated, and special techniques have developed for the bacteriological examination of air.

Dust. A complete study of the dust in the air involves a *dust count* of numbers of particles, classified into size groups; microscopic examination and classification as to nature, into fibers, silica, steel, and so on; and frequently chemical examinations for the estimation of lead, and similar processes. The methods employed in the collection of a sample may depend on impingement, filtration, or electrostatic precipitation.

The *impinger* is widely used for the collection of certain industrial dusts. In the Greenburg–Smith impinger, air drawn into the apparatus passes through a small-bore tube and impinges at high velocity against a glass surface under water. The aqueous suspension resulting from the passage of a known volume of air is diluted, and an aliquot sample is examined by microscope. The particles are counted and classified as to size and characteristic shape.†

Chemical Analysis. The dusts collected in the impinger or by other methods of sampling may be submitted to chemical analysis.

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* Made by Illinois Testing Laboratory, Inc., 422 North LaSalle Street, Chicago, Ill.

† J. J. Bloomfield and J. M. Dalla Valle, *U. S. Pub. Health Service, Pub. Health Bull.* **217**, 1935.

This is of special interest in the examination of stone dusts for percentage of free silica and of dusts carrying lead or other harmful metals.

Vapors, such as those of benzole, and gases, such as carbon monoxide, are absorbed in suitable chemical reagents or in water, by measured quantities of the air being passed through the absorption apparatus. The solutions are submitted to appropriate chemical analyses.

Bacteriological Examination. Various methods for the examination of air for suspended bacteria have been suggested. Filtration through fine sand and through sugar yield only approximately quantitative results. The Wells air centrifuge* passes a measured stream of air through a rapidly whirling cylindrical glass tube, the sides of which have been coated with a prepared nutrient agar. The bacteria are projected by centrifugal force against the agar where they are held and develop as on the Petri dish. The quantitative recovery ranges from nearly 100 per cent for the larger suspended matter down to the order of 33 per cent for the fine nuclei produced by spraying.† Mere exposure of Petri plates for periods of one-half to several hours gives relatively quantitative counts of the bacteria which settle.

EQUIVALENT CONDITIONS

It is a matter of common experience that the body is warmed and cooled by many separate environmental conditions. We feel the warmth of the fire in the open fireplace, the discomfort of a hot muggy day, and the relief that comes from an electric fan. Obviously, the various agencies of warming and cooling act together, and there must be sets of conditions which, although differently constituted, provide the same measure of net cooling for the body. These may be termed equivalent conditions.

The author once set up an experiment in which the rate of heat loss from a moist sheepskin surface, maintained at constant temperature, could be accurately measured under controlled conditions of air temperature, humidity, and movement. The data, shown in Table 4, represent the relation that was derived from the statistical analysis

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* W. F. Wells, *J. Am. Pub. Health,* **23,** 58, 1933.

† E. B. Phelps and L. Buchbinder, *J. Bact.,* **42,** 321, 1941.

of some 1000 observations under a wide range of variation of the three variables.*

It should be noted that this was a purely physical experiment free of any complications from physiological reactions of the "subject." The data however represent sets of equivalent cooling conditions for a moist skin surface, backed by water at 37 degrees centigrade. Air velocities are relative and may be taken in any unit. If they represent centimeters per second, the rate of cooling under any combination of the three variables is 0.361 gram-calorie per second per square centimeter.

TABLE 4

EQUIVALENT CONDITIONS OF ATMOSPHERIC TEMPERATURE HUMIDITY, AND MOVEMENT, WITH RESPECT TO HEAT LOSS FROM A MOIST SHEEPSKIN SURFACE

Relative Velocity of Air Movement	Air Temperature °C					
	10	15	20	25	30	35
	Relative Humidity of Air, Per Cent of Saturation					
1.00	50.0	21.3	13.4	4.9	..	..
1.39	100.0	63.8	40.5	25.2	15.2	8.6
1.55			50.0	32.6	21.2	12.8
1.77			60.0	39.8	26.3	17.1
2.04			70.0	47.3	32.0	21.4
2.37			80.0	54.8	37.6	25.8
2.75			90.0	62.3	43.3	30.1
3.24			100.0	69.8	49.0	34.5
4.58				84.4	60.0	42.9
7.0					75.0	54.3
15.40					90.0	65.8
26.60					100.0	73.5

Equivalent cooling conditions with respect to the human body are not so readily evaluated. The *cooling power* of the air, is determined by the conditions of the body to be cooled as much as by the physical properties of the air itself. The skin temperature and the amount of sweat available for evaporation are especially significant variables. Nevertheless various attempts have been made, with more or less success, to represent air conditions with respect to body cooling by a single index.

THE KATA THERMOMETER. This is an instrument devised by Dr. Leonard Hill for measuring the cooling power of the air. It consists

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* *Ventilation,* chapter XIV.

of a large-bulb thermometer with marks on the stem at 100 degrees and at 95 degrees Fahrenheit, that is, a 5-degree range centered at about the temperature of the human body.

It is heated in hot water to something over 100 degrees, quickly dried, and suspended in the air. With a stopwatch the time is taken between the successive crossings of the two marks by the descending column of the thermometer. This time, divided into the instrumental constant, etched on each instrument, gives the cooling rate in millicalories per square centimeter per second.

Cooling in this instance is by conduction and convection (plus some radiation), and equivalent cooling conditions (same time of cooling with respect to the dry Kata thermometer) may be found, covering a wide range of individual variations. A *wet Kata* reading is made in the same manner with the thermometer bulb covered with a moist silken sleeve. This integrates the cooling due to evaporation with the other terms.

There are several other special devices which integrate two or more of the air conditions to give a combined measure of the equivalence of different sets of these conditions with respect to cooling of the particular device.

THE GLOBE THERMOMETER. This consists of a blackened copper ball, 6 inches in diameter, within which the thermometer bulb is located. It is affected by radiation to and from the surrounding walls, as well as by air temperature. Air movement tends to reduce the relative influence of radiation. It does not measure the rate of cooling of a warm body, but, if, in addition to the globe-thermometer reading, the air temperature and air movement are measured, it is possible to compute the equivalent conditions.

THE EUPATHOSCOPE. Dufton's eupathoscope is a blackened copper cylinder, the outer surface temperature of which is maintained at 75 degrees Fahrenheit by electric lamps. The heating current also heats a thermometer bulb the readings of which, compared with readings under certain standard conditions, provide an *equivalent temperature* scale, or scale of relative cooling as influenced by air temperature and movement as well as by radiation.

THE THERMOINTEGRATOR. This apparatus, developed by Winslow and associates at New Haven, is similar to the eupathoscope except that, instead of having a constant surface temperature, it is supplied with a constant heat input. The surface temperature then varies with the air temperature and movement and with the radiation, somewhat as does the skin temperature of the body although much more so.*

These instrumental measures of the combined effect of the various heating and cooling agencies, operating in any given combination, fall short of providing specifications for a satisfactory air in several ways. None of them, for one thing, actually simulates the human body. Hill, for example, expressly disclaims that the rate of cooling of the *Kata thermometer* is the same per unit area as that of the human body under similar air conditions, or that it is affected by the independent variables to the same relative degree. Probably the *themointegrator* more nearly approaches the reactions of the human body to the combined cooling influences of radiation and air temperature and movement than do any of the others.

Effective Temperature. The foregoing measures of the cooling conditions of the environment are all instrumental and thus objective. The *effective temperature* scale, developed in the research laboratories of the American Society of Heating and Ventilating Engineers, is based upon the criterion of the subjective sensation of warmth. Airs, contained in two adjacent rooms, have the same effective temperature if a subject, in passing quickly from one to the other, feels no sense of temperature change.

As originally defined and numerically evaluated, the *effective temperature* of an air condition is the temperature of still air, fully saturated, which induces an equal sensation of warmth. Because we are not accustomed to interpreting the sensation of exposure to saturated air, a new expression, the *normal effective temperature,* has more recently been adopted. It is defined like effective temperature except that the basis of reference is air at 50 per cent relative humidity.

Figure 4 illustrates the relation between effective temperature and the temperature and humidity of the air. This is for still air and with subjects normally clothed and at rest. The 71° effective-temperature line, for example, passes through the points 78.8°–30% and 73.8°–70%; if extended, it would also pass through the point 71°–100% by definition. It cuts the 50% relative-humidity line at 76.2°, the *normal effective temperature* corresponding to *effective temperature* 71°.

SIGNIFICANCE OF EQUIVALENT CONDITIONS

A defect in any of these combined measures of cooling power is that they integrate cooling power whereas the body feels separately

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* C.-E. A. Winslow and L. Greenburg, *ASHVE Trans.*, 41, 149, 1935.

the effects of the various cooling agencies. While maintaining under all ordinary conditions a thermal balance with the environment, it responds quickly to the various different means of cooling. Thus, what is physically equivalent is not in any sense physiologically equivalent. The concept of equivalent conditions ignores this basic physiological fact upon which the whole matter of body cooling and body comfort rests.

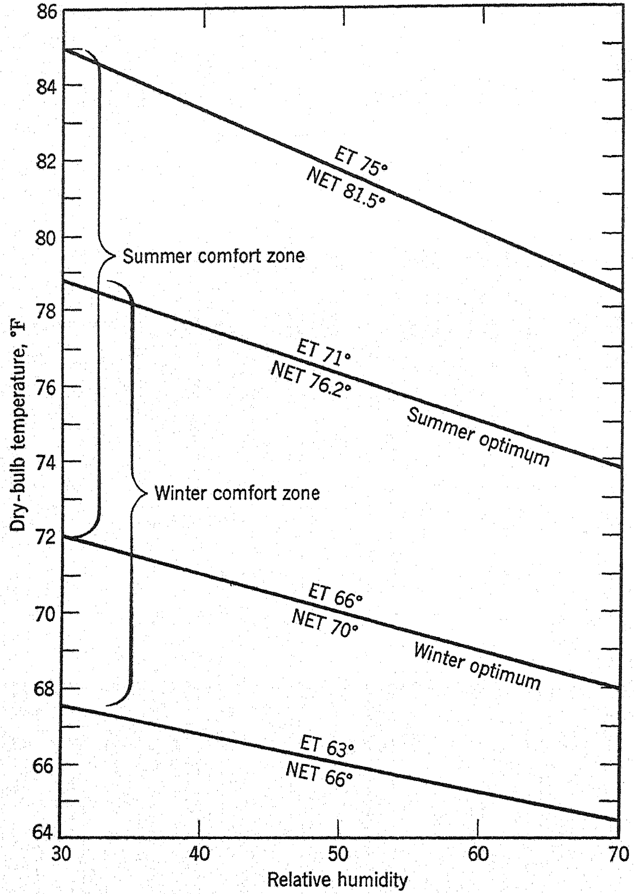

FIG. 4. Relation between temperature and relative humidity of the air and "effective temperature" (ET) and "normal effective temperature" (NET). Summer and winter optima and ranges for human comfort. (ASHVE data)

It is found, in fact, that, for any particular age and occupation, such as young children at school, and with appropriate clothing, there is an optimum air condition, fixed within rather narrow limits, as to temperature and velocity of movement and temperature of the surrounding walls. In this specified group and under these conditions, perspiration is of the insensible sort, evaporation is complete within wide ranges of humidity, and variations of humidity do not affect the rate of cooling.

On the other hand, in a group of mechanics, engaged in active labor in warm air, the optimum condition is further restricted to a humidity sufficiently low to permit cooling by evaporation of the sensible perspiration which accompanies their greater activity and higher body temperature.

OTHER CRITERIA

There are two other criteria of room conditions to which reference must be made. These are the sensations of comfort and the statistical record of health or freedom from illness on the part of the group.

COMFORT

The *comfort reaction* is a more critical subjective criterion than any thus far discussed. In a group, such as a school class, a comfort vote may be taken on a numerical basis by using some such scale as that employed by the New York State Ventilation Commission. Vote number three indicated comfort, neither too warm nor too cool. Two was slightly, and one, decidedly, too warm; four, slightly, and five, decidedly, too cool. Similar votes were taken for moist and dry, fresh and stuffy, and so on. The numerical average of the class votes represents the average reaction.

The uses to which the comfort vote may be put are well illustrated in the work done by Bedford in his studies of factory conditions made for the Medical Research Council of the British Ministry of Health. Bedford collected comfort votes from some 2571 factory workers, mostly young women doing light or sedentary work. At the same time he recorded the physical conditions in the usual terms, temperature, humidity, and movement, and in terms of several of the measures previously described for evaluating two or more room conditions in terms of cooling power. The latter included the

Kata thermometer, eupathoscope, globe thermometer, mean radiant temperature and effective temperature.

These data were submitted to statistical analysis in the form of correlation tables in which each of the instrumental measures was separately compared with the comfort vote. Table 5 shows the correlation observed between temperature and individual comfort votes.

TABLE 5

COMFORT VOTES AND AIR TEMPERATURE
Bedford—English Factory Workers

Temperature, °F	Comfort Votes							Total
	1	2	3	4	5	6	7	
54–56	..	..	..	6	1	5	1	13
56–58	..	..	1	43	23	18	2	87
58–60	..	..	1	70	31	27	2	131
60–62	..	..	5	296	42	38	14	395
62–64	..	10	7	503	43	41	4	608
64–66	..	12	16	317	39	15	..	399
66–68	..	29	53	297	24	13	1	417
68–70	5	41	103	199	1	..	..	349
70–72	1	25	56	58	1	..	..	141
72–74	3	2	4	13	1	..	..	23
74–76	3	4	..	1	..	..	..	8
Total	12	123	246	1803	206	157	24	2571

Meaning of comfort votes:

1. Much too warm.
2. Too warm.
3. Comfortably warm.
4. Comfortable.
5. Comfortably cool.
6. Too cool.
7. Much too cool.

One notes first the great diversity of reaction. Six out of 13 votes at 54–56 and 13 out of 23 at 72–74, recorded "comfortable." This probably represents individual preferences, differences of clothing, and the like. There is, however, some correlation indicated, since at the low temperature the "noncomfortable" votes were all on the cool side and at 75 degrees they were on the warm side. Moreover, the maximum proportion of "comfortable" votes was at 62–64 where they constituted 83 per cent of the total votes at that temperature. It is of interest also to note that this temperature range was found much more frequently than any other, as indicated in the last column. This may mean that the workers dressed for and had become accustomed to this particular temperature, the prevalent one in the factories studied, or that temperatures were adjusted in most of the factories to the wishes of the workers.

Correlation is indicated by the approach to a diagonal distribution of the data across the table. The closer this approach, the higher the degree of correlation and the more reliable the thermometer reading as an index of comfort. The correlation coefficient is determined by statistical treatment of the data and measures the degree of correlation in a single numerical value upon a scale in which unity represents perfect correlation.

The coefficient in this example is 0.48. Comparison of comfort with the effective temperature scale, which includes the humidity, gave an identical coefficient. This indication of the negligible effect of humidity upon the sensation of comfort within the temperature range of this record is supported by a very low correlation between comfort and humidity itself, minus 0.12. Only those instruments which include radiation, the eupathoscope and the globe thermometer, showed better correlation with comfort than did the air temperature, 0.52 and 0.51, and these differences are hardly of statistical significance. Under these conditions the air temperature appears to be as reliable an index of comfort as any of the other, more complicated measures.

The comfort vote indicates only a statistical array of exceedingly diverse opinions. This is both its strength and its weakness. It reflects the true state of affairs which happens to be complicated. Thus, as previously noted, "comfortable" was voted by some throughout the temperature range 55–75 degrees, and at 62–64 degrees, when about five sixths of those voting were comfortable, the votes ranged from too warm to much too cool.

This individual variability is unavoidable. It depends upon many things such as age and sex (most of these workers were young women), clothing, health, condition of nourishment, and, very largely, personal habits and local customs. It would hardly be expected that 83 per cent of a group of factory workers, mostly women, doing light or sedentary work in the United States would be comfortable at 62 to 64 degrees or three fourths of them, at 60 to 62 degrees. The author noted some years ago, in attempting to correlate comfort with various measures of cooling, that a much warmer temperature was preferred by a laboratory group in Washington, D.C., than by a similar group in Boston.

The second shortcoming of the comfort vote, possibly linked with the previously noted observation, is the questionable relation between comfort and hygiene or healthfulness. Do overheated homes, offices, and classrooms tend to soften one's resistance and to make one choose an unhygienic condition as the more comfortable? Without attempting to go beyond the mere statement of this question we certainly cannot answer it negatively. Comfort cannot be identified with healthfulness any more than can the attractiveness and flavor of foods.

In connection with the extensive investigations made in the research laboratories of the American Society of Heating and Ventilating Engineers (ASHVE) and elsewhere under the sponsorship of that organization, the subject of comfort has received considerable study. Figure 4 has been drawn from some of their data.

The two comfort zones, for summer and winter, respectively, represent the results of comfort votes; roughly 50 per cent of the persons expressing an opinion were comfortable at the limits, and 97 or 98 per cent at the optimum point. Note, however, the wide limits of the range, about 10 degrees, within which at least half of the room occupants felt comfortable. Presumably very few individuals were comfortable at both limits, but at least half of them showed no preference as between the optimum and the lower limit, a 5-degree range, while the other half were similarly tolerant within the 5-degree range between the optimum and the upper limit.

An interesting point is the difference, about 6 degrees, between summer and winter optima. This is partially a matter of clothing and partially one of acclimatization. In either event it is seasonal; the optimum makes an annual to-and-fro movement between these limits.

THE HEALTH CRITERION

Appropriate health records constitute the ideal criterion of air and room conditions. They involve much time and effort and, to be of real value, some degree of medical supervision. The health criterion was employed in the studies of the New York State Ventilation Commission to the extent of recording, in the various experimental and test classrooms, *absenteeism due to colds* and *colds (sniffles) in attendance.* The first was merely the home report of the cause of absence; the second, the school nurses' diagnosis. Although far from perfect, these data, in large numbers, yielded statistical values of considerable worth and significance.

In certain later studies the school physician investigated each case of absenteeism and of colds in attendance. At the other extreme, much useful information can be had, especially if large groups of similar make-up are compared, by merely noting absenteeism. This has been done among telephone operators in large exchanges. A double control is available; comparative data on absenteeism over a period preceding the experiment, and again comparison with a control group during the experiment. The first of these indicates the degree of similarity between the two groups under the same environment; the second, any change occurring after changing one of the environments.

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CHAPTER 4

THE THERMAL ENVIRONMENT OF THE HUMAN BODY

In the concise statement, previously quoted, "The problems of ventilation are physical, not chemical; cutaneous, not respiratory," Professor Lee has summed up the facts and pointed to the major objective of ventilation as we know it in connection with the home and the school. It is true that there are many industrial situations in which chemical pollution of the air constitutes a health hazard and which require correction. These situations will be dealt with in the proper place. It is true also that a better understanding of the possibilities of air-borne infection has drawn attention to the bacterial impurities of the air and their hygienic significance. This phase of air control will also require attention.

A REVIEW OF SOME PHYSICAL LAWS

For the present let us consider some of the principles that underlie the theory and the practice of ventilation as it is undertaken to control the thermal environment of the human body. To this end it will be helpful to review some of the physical laws concerning gases and the nature and the transfer of heat.

THE GAS LAWS

The laws which govern the behavior of gases under varying conditions of temperature and pressure can be expressed in very simple terms. In modern times physicists have greatly refined and complicated these laws, but our present purposes will be best served by considering them in the forms in which they were originally stated and under the names of their original scientific sponsors.

BOYLE'S LAW. If the temperature of a fixed quantity of gas remains unaltered, any change in its pressure is accompanied by an equal and opposite change in its volume, and vice versa. Thus, if the pressure is doubled, the volume is halved. In other words, at constant temperature the pressure–volume product of the gas remains constant. This relation is known as *Boyle's law.*

Charles's Law. The constant pressure–volume product itself is a function of temperature. A gas heated at constant pressure, that is, allowed to expand, increases in volume by 1/273 of its volume at zero degrees centigrade for every one degree increase in temperature. If heated at constant volume, that is, in a closed container, its pressure increases in the same manner. This is *Charles's law.*

This observation is in harmony with the concept of an absolute temperature scale, the zero of which is at minus 273 degrees centigrade. On such a scale the pressure–volume product of any fixed quantity of a gas is always proportional to its absolute temperature. This scale is known from its author as the *Kelvin scale.* It is related to the centigrade scale by the identity of the two points:

$$0°\text{C} = 273°\text{K}$$

and

$$100°\text{C} = 373°\text{K}$$

The Generalized Gas Law. The restriction as to fixed quantity of gas, made in the foregoing discussion, may be readily removed, in the case of any given gas. If 2 liters of the gas be compressed to one liter, half its initial volume, its pressure is doubled. Thus the pressure is proportional to the amount of gas in any given volume. This rule may be further generalized by the application of *Avogadro's law* which states that equal volumes of all gases at the same temperature and pressure contain equal numbers of molecules. That is to say, gas pressure is a matter of number of molecules of gas regardless of molecular weight.

Summarizing, we may write

$$pv = nRT_{\text{K}}$$

which merely states that the pressure–volume product is proportional to the number of molecules present, n, and to the absolute temperature T_{K}. The proportionality factor, R, known as the gas constant, merely ties together the various units employed in the other terms. If the pressure is measured in atmospheres, the volume in liters, and n in gram-molecules (weight of the gas in grams divided by its molecular weight), the gas content has the value 0.082.

Partial Pressures. Assume, for simplicity, that air is one-fifth oxygen and four-fifths nitrogen (by volume). In the jar, Figure 5, obviously it will make no difference in the pressure if the two gases could be segregated as pictured. Now if the oxygen be removed, as can readily be done by chemical reaction, the nitrogen will expand to fill the entire space, and its pressure will be reduced inversely as four to five, or to 80 per cent of its initial value. Similarly, removal of the nitrogen would leave the oxygen at a pressure of 20 per cent of the initial pressure.

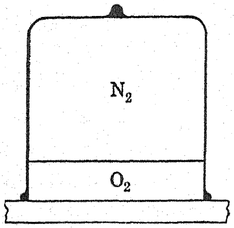

Fig. 5. Diagrammatic illustration of partial pressure in a mixture of gases (air).

These are the partial pressures of the two gases in the air. In general and in any gas mixture, each gas is under a partial pressure the relation of which to the total pressure is the same as its volumetric percentage in the mixture. Stated in another way, each gas follows the gas law as to its volume and *partial pressure,* regardless of the presence of other gases in the same space, and the total pressure in any gas mixture is the sum of the partial pressures of its components.

In connection with Table 2 (p. 41), which shows the partial pressure of saturated aqueous vapor in air, it was stated that these values represented "somewhat imperfectly" the concentration of the vapor in the air expressed in volume per cent. Aqueous vapor is not strictly one of the *perfect gases* which conform closely to the law of partial pressures, but for most purposes and within the range of temperatures dealt with in ventilation problems the relation may be assumed to hold with sufficient approximation. At 20 degrees, for example, saturated aqueous vapor, the density of which is 0.0173 gram per liter would, according to the gas laws, exert a partial pressure of about 2.26, as compared with the tabulated value 2.32.

THE LAWS OF HEAT TRANSFER

Temperature and Heat. Temperature is thermal potential. It is to heat what pressure is to a gas or a liquid. The hydraulic analogy is, in fact, so perfect that it will serve to illustrate the less well-known facts concerning temperature and heat and the flow of heat.

Let us connect two vessels, *A* and *B* (Figure 6), with a small-bore pipe. Partially fill the system with water. The water in the two vessels will eventually stand at the same elevation above any given base plane. Elevation, in this case, means pressure, likewise measured at the arbitrary zero level of the base plane. Equilibrium is only possible when this pressure is equalized.

Now add water to *A*. Water flows into *B* to a new equilibrium. The *rate* of flow is determined by the difference in elevation (pressure), and by the conductivity (inverse of resistance) of the connecting system. It is independent of the sizes, actual or relative, of the two vessels.

Let elevations in the two vessels represent temperatures; the masses of water, heat. *Temperatures of two bodies, in thermal contact, tend to equalize by a flow of heat from the higher to the lower temperature. The rate of flow is proportional to the difference in temperatures (thermal pressure) and inversely to the thermal resistance of the connecting system.*

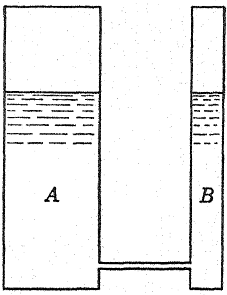

FIG. 6. Hydraulic analogue of heat, temperature, and thermal capacity.

HEAT UNITS. In the preceding discussion heat has been dealt with as if it were a substance. This is a useful convention. Heat is measured in quantity units just as water is. The unit quantity of heat in the cgs system, is the *gram-calorie* or *small calorie*. This is defined as the quantity of heat required to raise the temperature of one gram of water from 15 to 16 degrees centigrade. The hydraulic analogy indicates that this is equivalent to the amount of heat contained in one gram of water *between the levels 15 and 16 degrees.* This latter is the more useful mental concept of the calorie.

The large or *kilogram-calorie* refers to the kilogram of water and is equivalent to 1000 gram-calories. The Btu (British thermal unit) refers to the pound of water and the Fahrenheit degree. One British thermal unit is equivalent to 0.252 kilogram-calorie.*

SPECIFIC HEAT. With reference again to the experiment illustrated in Figure 6, the *amount* of water which must flow to equalize the pressures is determined by the cross-sectional dimensions of the two

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* To avoid confusion it should be noted that to the physicist the calorie means the small or gram-calorie, whereas the physiologist and the nutritionist generally employ the same term without qualification when the large or kilogram-calorie is meant. Thus in current popular discussions of diets a daily intake of food having a calorific value of 2000 means 2000 kilogram-calories.

vessels as well as by the difference in their water-surface elevations. If the cross-sectional areas of the two vessels be as ten to one, then 11 volumes of water added to A would result in the transfer of 1 volume to B; 11 volumes added to B would result in a transfer of 10 volumes to A.

Matter has an analogous thermal dimension known as its *specific heat* and defined as the heat, in gram-calories, required to raise one gram of the substance through one degree centigrade. The gram-calorie being the amount of heat required to raise the temperature of one gram of water from 15 to 16 degrees, the specific heat of water at this temperature becomes unity, and other specific heats, therefore, are relative to that of water.

Complete analogy with the hydraulic system requires one further dimension, the *thermal capacity* of a mass which may now be defined as *the heat required to raise the temperature of the mass one degree.* Thermal capacity is obviously weight, in grams, times specific heat.

A few specific heats are given in Table 6 for illustration.

TABLE 6

SPECIFIC HEATS OF SUBSTANCES*

Substance	Specific Heat
Copper	0.093
Iron	0.113
Glass	0.2
Air	0.24
Water, 15–16°C	1.0

*Except for water the values are mean specific heats between 0 and 100°C. The specific heats vary slightly with the temperature.

A numerical example will clarify these relations. To one kilogram of water at 15 degrees add 100 grams of iron at 200 degrees. If there be no heat lost during the operation, what will be the resultant uniform temperature of the mixture?

Thermal balance requires that the gain of heat by the water will equal the loss of heat by the iron. Gains and losses are measured by mass times specific heat times temperature change. If we let t represent the final temperature of the system

$$1000 \times 1 \times (t - 15) = 100 \times 0.113 \times (200 - t)$$

giving

$$t = 17.1$$

THERMAL CONDUCTION. The transfer of heat through material bodies is termed *conduction*. It is a molecular phenomenon. Heat, basically motion, is transferred from the faster to the more slowly moving molecules upon contact. The tendency, therefore, is always in the direction of equalization of velocities, that is of temperatures. Thus, if one end of a conductor is heated, heat travels toward the other end.

The law of conduction is expressed by the partial-differential equation:

$$\frac{\partial Q}{\partial t} = hA\frac{\partial T}{\partial x}$$

which states that the rate at which heat Q passes through any cross-section, perpendicular to the direction of flow, is proportional to the cross-sectional area A and to the rate at which the temperature T is changing along the axis of flow, that is, the thermal gradient, $\partial T/\partial x$.

The proportionality constant h is the coefficient of conductivity. It defines the *thermal conductivity,* as a physical property of the substance. The reciprocal of conductivity is thermal resistance or nonconductance, more commonly, insulating power.

Thermal conductivity is somewhat akin to electrical conductivity. Metals, as a class, are good conductors of heat; glass is a good insulator. Gases, in particular, presumably because their molecular pattern is one of wide spacing, are very poor conductors. Many of the best insulating materials, cork, balsa wood, fur, have little solid mass and a high degree of porosity. The contained air spaces contribute materially to the insulating power.

The coefficient of conductivity h is numerically related to the system of units chosen for the other dimensions. In the cgs system the equation defines the coefficient as the rate of heat passage, in gram-calories per second, through an area of one square centimeter under a thermal gradient of one degree centigrade per centimeter of length. A definition more readily visualized is the rate of heat transfer through a one-centimeter cube, the opposite faces of which are maintained at temperatures one centigrade degree apart.

A few typical conductivities are given in Table 7.

A point of practical interest is the advantage which an aluminum

TABLE 7

THERMAL CONDUCTIVITIES OF CERTAIN SUBSTANCES

Substance	h (Cgs System)
Silver	1.006
Copper	0.918
Aluminum	0.480
Cast iron	0.108
Glass, (window)	0.0025
Air	0.00006

cooking utensil possesses over one of cast iron and the even greater advantage of the old copper or copper-bottomed kettles now so completely replaced by aluminum.

American and British engineers specify thermal conductivity in the units Btu (British thermal unit) per hour, per square foot, per gradient of one degree Fahrenheit per inch. This expression is better adapted to the measurement of heat losses through the walls of buildings or of boilers. Values of the coefficient h in these units are 2903 times those given in the cgs system.

THE THERMAL GRADIENT. The thermal gradient is the slope down which the heat flows or

$$\frac{dT}{dx}$$

which may be evaluated in any convenient units. Under conditions of uniform heat flow through the body the gradient is merely the *temperature difference divided by the distance.*

In Figure 7 the bar has a length of 1 meter. One end is maintained at 20 degrees and the other at 10 degrees. The gradient is then 1/10 degree per centimeter. If the temperature of the warm end be now raised and held at 30 degrees, the gradient will become 2/10 degree per centimeter, and twice as much heat will pass; or, from the point of view of body cooling, twice as much heat must now be supplied internally to maintain the same external (skin) temperature.

Note also that the same doubled gradient now exists in the right half of the bar, the warm end of which is now at 20 degrees. That is, by maintaining the same end temperatures and halving the length we have likewise doubled the gradient and the rate of heat flow.

Finally, the amount of heat transferred is proportional to the coefficient, *h*. The conductivity of a metal bar cannot be modified radically, but we shall see that, in human physiology, all three of these methods of modifying the rate of heat transmission are employed: changing the end temperatures, the thickness of the intervening medium, and its thermal conductivity.

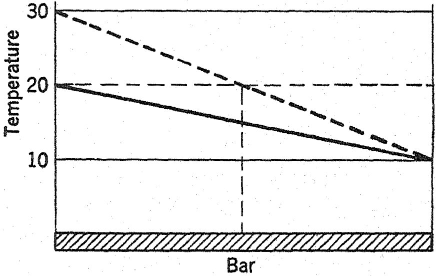

FIG. 7. Thermal conduction through a bar.

THERMAL CONVECTION. Cooling of the human body by conduction alone would be a slow and inadequate process. Conduction would take place first at the surface of contact between skin and air. This would quickly heat the adjacent layer of air up to skin temperature, and further cooling would be by conduction through the air which is a poor conductor. If the surrounding air could be held in place it would constitute almost perfect insulation.

If, however, this warm surface layer is being continuously removed and replaced by fresh cool air, the process of heat transfer is continuous. This is transfer by *convection*. Rising convection currents, having a velocity of about 25 feet per minute, are normally established over the body in otherwise quiescent air. Additional air movement, induced by fans or by general air circulation, further contributes to the cooling power of the air.

Cooling by the combined agencies of conduction and convection is best dealt with as a single function, related to the difference between skin and air temperatures and to the extent of air movement. Experimental studies have shown that, within the range of usual environmental conditions, the rate of body cooling by these agencies is expressed by

$$\frac{dQ_c}{dt} = k_c A \sqrt{v}(T_s - T_a)$$

The rate of heat interchange is proportional to the exposed area A, to the square root of the velocity v of air movement, and to the difference between the skin and air temperatures T_s and T_a. The proportionality constant k_c involves the various units of measurements of the other dimensions. Its numerical value under certain experimental conditions is discussed in a later section.

It is to be noted that, whereas conduction alone would provide almost no cooling, owing to the nonconducting property of the air, still conduction between the skin and the adjacent air layer is the basic process. The formula indicates that there is a steep gradient at the surface, represented by the temperature difference, $T_s - T_a$, across a thin film of air. The thickness of this fixed air film is determined by the velocity of air movement beyond. As shown in Figure 7, the thinner this film, the steeper is the gradient and the greater the rate of conduction.

RADIATION. A third mode of heat transfer is by radiation. This represents the passage of energy through space without the aid of material substance. It is the means by which solar heat (and light) are brought to the earth. It is obstructed by matter, slightly so by the pure air, noticeably by smoky or foggy air, and completely by opaque bodies. Opacity, however, must be defined in terms of the specific wave lengths under consideration. Most glass obstructs the passage of the short waves of ultraviolet radiation, and aqueous vapor in the atmosphere interferes with the passage of certain long-wave (heat) radiation. The air itself cuts out ultraviolet radiation below a certain wave length. We may note also the considerable transparency of the human body to X rays, to which metals are relatively opaque.

As a cooling—or warming—mechanism for the human body, radiation depends upon the temperature of the surrounding *radiation sphere,* which is the projection, upon a spherical surface about the body as a center, of all surrounding walls, windows, floor, and ceiling. The mean temperature of these projected surfaces constitutes the *mean radiation temperature* and determines *in toto* the rate of radiant-heat interchange between the body and its surroundings.

Every mass radiates heat at a rate which is proportional to the fourth power of its temperature on the absolute or Kelvin scale, the zero of which is at —273.1 degrees centigrade. As between two opposed surfaces, skin s, and walls w, each radiating to and receiving radiation from the other, the net interchange at the body, area A

square meters, will be

$$\frac{dQ_r}{dt} = \beta A(T_s^4 - T_w^4)$$

in which T_s and T_w are absolute temperatures of the skin and the walls, respectively, and β is the Stefan–Boltzman constant, 4.92×10^{-8} kilogram-calorie per hour per square meter.

The temperatures in which we are now interested lie within a relatively restricted range and are of the order of 300 degrees Kelvin. Within this range we may, for practical purposes, substitute the first power of the centigrade temperatures, as is seen in the comparative values in Table 8.

TABLE 8

Radiation Values (Relative)

Exposed skin temperature 32°C = 305°K

Wall temperature, °C	0	10	20	30	40
Wall temperature, °K	273	283	293	303	313
$T_s - T_w$, °C	32	22	12	2	—8
$10^{-8} \times (T_s^4 - T_w^4)$, °K	31	22.4	12.8	2.2	—9.4

Between 0° and 32°, therefore, we may write with sufficient approximation,

$$\frac{dQ_r}{dt} = 5A(T_s - T_w)$$

as the rate of heat loss, kilogram-calories per hour, from a body exposure of A square meters with skin and wall temperatures T_s and T_w, °C, respectively.

Evaporation. Finally, heat is transferred as *heat of vaporization*.* Evaporation is governed by the humidity of the air, its aqueous vapor content. Other things being equal, evaporation from unit area of a free water surface is proportional to the *saturation deficit* in the space above.

This rule of the deficit is one of rather frequent occurrence. It will be met in various forms in subsequent chapters and its significance is rather fundamental. It can be represented by a mechanical analogue.

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* The older terms, *latent heat* and *insensible heat,* now generally avoided in conventional thermodynamics, are still in common use in the literature of air conditioning.

In a spring balance the extension of the spring is proportional to the pull exerted. Given such a balance (Figure 8), let the position of the pan at no load be marked 100, and some other position, corresponding to a load of 100, be marked zero, on an auxiliary scale which represents in general, per cent saturation or, in this instance, relative humidity. A pull exerted on the spring as indicated on the dial now represents the evaporative pull or tendency corresponding to the air condition indicated on the saturation scale. The *rate* of evaporation is proportional to that pull and thus to the saturation deficit.

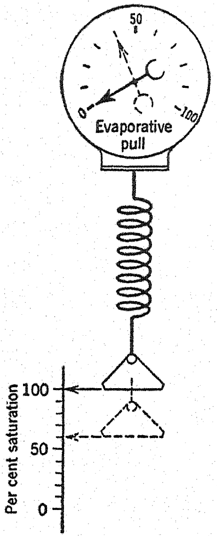

FIG. 8. Mechanical analogue of the rule of the deficit pull.

Some of the "other things" held constant in the foregoing illustration of the rate of evaporation as a function of saturation deficit are temperature and rate of air movement. Not only does temperature determine the saturation value (Table 2), but also at a given deficit evaporation is more rapid at the higher temperature owing to the increased mobility of the water molecules, both as liquid and as vapor.

The effect of air movement is precisely that previously found upon conduction. The fundamental reason for this is that the molecules of vapor diffuse from the actual evaporating surface, where saturation may be presumed to exist, through a thin film of air to a region where the air conditions are maintained by convection. The laws of gas diffusion have exactly the same form as those of thermal diffusion. The diffusion gradient may be defined as the difference in humidity between the saturated contact film and the outer air: that is, the saturation deficit. The gradient, however, is also determined by the film thickness, which as we have seen previously, is determined by the velocity of the convection current.

The importance of evaporation as a cooling mechanism is due to the fact that heat is absorbed and disappears during evaporation, only to reappear upon subsequent condensation. This heat represents the energy of expanding the liquid to the gaseous phase. A few values of the heat of vaporization are given in Table 9, together with values of the density (weight per unit volume) of saturated aqueous vapor.

TABLE 9

HEAT OF VAPORIZATION OF WATER AND DENSITY OF SATURATED AQUEOUS VAPOR, AS FUNCTIONS OF TEMPERATURE

Temperature		Heat of Vaporization		Density	
°C	°F	$\frac{\text{Kg-Cal}}{\text{Kg}}$	$\frac{\text{Btu}}{\text{lb}}$	$\frac{\text{gm}}{\text{cu m}}$	$\frac{\text{grain}}{\text{cu ft}}$
0	32	595	1072	4.85	2.12
5	41	593	1067	6.80	2.97
10	50	590	1062	9.41	4.12
15	59	588	1058	12.8	5.61
20	68	585	1053	17.3	7.58
25	77	582	1048	23.0	10.0
30	86	580	1043	30.4	13.2
35	95	577	1039	39.6	17.3

It is seen that heat of vaporization is a temperature function. In the region of normal skin temperature, 32 to 34 degrees Fahrenheit, it is customary and quite satisfactory to take the value 580 kilogram-calories per kilogram of water evaporated (or 1043 Btu per pound) in the computation of heat losses. If we recall the definition of the calorie, it is apparent that the heat required to evaporate 1 gram of water would, if abstracted wholly from the body, be sufficient to lower the temperature of another gram of water through 580 degrees, or, more reasonably, to cool 580 grams of water through 1 degree. Thus evaporation is a potent cooling mechanism.

PHYSIOLOGICAL PRINCIPLES OF BODY HEATING AND COOLING

The processes of heat transfer discussed thus far have been illustrated by references to the conditions of body cooling. Nevertheless, they are purely physical processes and could equally well have been referred to simple inanimate objects. Basically, cooling of the human body is a physical process and is effected through the various physical channels that have been discussed. Beyond this, however, there are physiological requirements and physiological adjustments, both of which enter into and complicate the process. Some of these will be reviewed in this section.

METABOLISM

Definitions. The word *metabolism*, or *change* in its original Greek form, has several slightly different meanings. In general biology it is the continuous process of destruction (catabolism) and reconstruction (anabolism) of living tissue. The nutritionist studies the oxidation of ingested food: protein, carbohydrate, and fat, in terms of physiological chemistry and calories; whereas the experimental physiologist determines the rate of production of energy within the body and terms this the body's metabolism or metabolic rate. It is this latter aspect of metabolism that enters the problem of body cooling.

Basal metabolism is the rate of production of energy in the completely relaxed and resting body after overnight fasting. It can be measured directly in an enclosed calorimeter because there is no external work involved and the total energy of metabolism appears as waste heat. It is also computed indirectly from the volume and chemical analysis of the expired air with the aid of certain factors, experimentally established, which relate oxygen consumption, carbon dioxide production, and heat of combustion of foods.

The *metabolic rate* under normal conditions of bodily activity is the work done plus the waste heat produced. It is computed by the indirect method. The work may be measured independently and subtracted from the total. It is the heat by-product that is of chief concern in the problem of ventilation; but it must not be overlooked that much of the so-called work, such as benchwork in a machine shop, is expended wholly within the room and reappears as heat. Only such work as lifting pig-iron bars from the floor to a car, which is then removed, would permit the thermal equivalent of the work done to escape from the immediate environment.

Age and Size. The metabolism of the body increases progressively with its growth in size. The New York State Ventilation Commission tabulated the data in Table 10 upon the thermal output of school children of various grades.*

Body Area. A beautiful illustration of adaptation is disclosed in the last column of Table 10. Extensive studies have shown that basal

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* *Ventilation,* Report of the New York State Commission on Ventilation, Dutton, New York, 1923.

TABLE 10

METABOLISM OF SCHOOL CHILDREN

School Grade	Average Age, Years	Average weight, Lb	Average Heat Output per Hr	
			Btu	Kg-Cal per Sq M*
1	7	40	292	90
2	8	46	318	93
3	9	53	345	91
4	10	60	373	91
5	11	67	397	87
6	12	75	401	87
7	13	81	409	83
8	14	98	488	92
9	15	104	500	89
10	16	112	488	87

* Computed from other data on average weights and heights of school children.

metabolism is more closely correlated with body area than with age, weight, or height. The significance of this relation lies in the fact that cooling is essentially a surface phenomenon. Even these crude comparisons, with two sets of data from different sources, indicate that heat production during the active lives of school children is closely related to the surface area of the body through which heat must be dissipated.

Du Bois, who has accumulated extensive data of this sort, has proposed the following formula by means of which the surface area of the human body, a difficult dimension to measure, can be computed from the height and weight:

$$A = W^{0.425} \times H^{0.725} \times 72 \times 10^{-4}$$

A is the area in square meters, W the weight in kilograms and H the height in centimeters. Transformed into the units, pounds of weight and inches of height, the constant 72×10^{-4} becomes 0.01, again giving area in square meters, in which unit the scientific data on body cooling are commonly expressed.

PHYSICAL ACTIVITY. Some early data by Benedict and Carpenter[†] serves to illustrate the relation between metabolism and work. The surface areas of the subjects averaged about two square meters so that the total metabolism, in calories per hours was about double the tabulated values.

The sleeping value represents the minimum expenditure of energy

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[†] F. G. Benedict and T. M. Carpenter, *Carnegie Inst. Wash., Pub.* 261, 1918.

TABLE 11

Metabolism and Work (Benedict and Carpenter)

Activity	Metabolism, Kg-Cal per Sq M per Hr	Loss by Evaporation, Per Cent
Sleeping	35	27
Awake, quiet	40	21
Standing still	47	24
Work, cal per hr		
5–11	77	30
17–25	100	40
"severe"	130	49

required to maintain the internal work of the body. Increasing activity brings about an increase in metabolism but at a much higher rate. Thus, when the work was measured, an average production of about 8 calories of work, above the work of standing idle, required the expenditure of an additional 30 calories of energy, a mechanical efficiency of about 25 per cent. It is of interest also to note that this additional energy of moderate work is somewhat less than the total energy requirements of merely sleeping. Bedford* estimates the mechanical efficiency of the human machine at about 20 per cent. These values indicate the importance of the problem of body cooling, especially under industrial conditions. Between 70 and 80 per cent of the energy developed by man at labor goes into heat.

More recent data permit greater refinement of the work levels and better definition in terms of every-day occupations. The values in Table 12, from various published sources, have been adapted to a standard 175-pound man, body area, two square meters.

THERMAL BALANCE

The basic requirement in the heat relations of the human body is that there must be complete thermal balance. The output of heat within each rather brief time interval, must equal heat production.

It is true that the body has a certain limited capacity for storage and that temporarily it can tide over a period of unbalance. The specific heat of the body, as a whole, may be taken at 0.83. An 80-kilogram body then has a thermal capacity of

$$80 \times 0.83 = 66.4 \text{ km cal per } ^\circ\text{C.}$$

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* T. Bedford, *Med. Research Council,* Industrial Research (*Brit.*), *Rep. 76,* London, 1936.

TABLE 12

METABOLISM AND WORK

Metabolism, Kg-Cal per Hr	Occupation or Activity
120	At rest
150–200	Standing relaxed, hand sewing, tailoring
200–300	Rapid typing, ironing with 5-pound iron, shoe making
300–400	Level walking between 2.6 and 3.8 miles per hour
	Laundry work, carpentry, industrial painting
400–500	Heavy occupations such as stone working
500–600	Very severe exercise such as tennis and basketball
	Such occupations as heavy trucking and farming

At a metabolic rate of 200 calories per hour and without any heat dissipation, the mean body temperature would rise 3 degrees centigrade in an hour. A game of tennis, producing 500 calories per hour, would, with only 10 per cent unbalance, bring about a temperature rise at the rate of 0.75 degree per hour.

The so-called constant temperature of the body is only an approximate expression of the fact that body temperature tends to remain quite close to the *normal* point of the clinical thermometer. During the diurnal cycle of sleeping, eating, and working, however, it moves regularly over a range of about 1 degree centigrade and, during vigorous exercise, over even wider ranges. Despite the fact that *storage* is one of the terms in the equation of thermal balance, the major requirement, as previously stated, is that heat output must equal heat production.

A PHYSICAL MODEL. Let us set up a simple physical apparatus comprising an airtight copper box heated within by an electric lamp. A condition of thermal equilibrium or balance will soon be reached, whatever the outside cooling conditions. The temperature of the interior will rise to such a point that the thermal gradient through the enclosing sides, taken with the thermal conductivity of the box material, is sufficient to induce conduction through that material at the same rate as the rate of heat production.

If the box were of wood, of lower conductivity than metal, a steeper gradient would be required, and the internal temperature would rise to a higher level to bring about a balance; if the wood be now made thicker, a still higher temperature would result. Increasing the rate of heat production would also produce a steeper gradient, that is, higher internal temperature.

Physiological Adjustment. In the body a somewhat similar condition is met, with the added limitation that the internal temperature must remain essentially constant. Adjustments to maintain thermal balance must, therefore, be of the nature of those outlined; the thickness and the characteristics of the insulating walls are varied. As an offset to this limitation, the body is provided with a powerful cooling agency in evaporation, which was not utilized in the example of the box.

Heat is generated in the muscular system and carried off by the blood stream. Within the skin there is an extensive capillary system of blood vessels. When these are flushed and distended, a large volume of blood is brought close to the surface for cooling. When the capillaries are constricted, the blood circulates chiefly in the deeper skin layers. Recalling that the flow of heat by conduction is proportional to the thermal gradient and that the gradient between two points varies directly as the difference in temperature and inversely as the distance, we can see that in the cooling mechanism of the skin both factors are utilized. Warmer blood is brought nearer to the surface. This phenomenon is illustrated in Figure 9. Simultaneously, radiation to the surrounding walls, also proportional to the temperature difference, is increased by higher skin temperature, and the conductivity of the skin itself becomes greater as it becomes wetter with perspiration.

With increased muscular activity and still greater heat production, perspiration and evaporation at the surface become increasingly important as illustrated in Table 11. The lungs also take part in cooling both by convection and by evaporation. Exercise, which produces more heat by burning more fuel, draws upon the lungs for an additional supply of oxygen; increased depth and frequency of breathing automatically increase heat loss through the lungs, both directly and by evaporation.*

Thus, under conditions of increasing rate of heat production and constant environment, equilibrium is maintained by an increase in the thermal gradient through the skin, an increase in outer skin temperature raising the skin–air and the skin–wall gradient, and increased evaporation.

Somewhat parallel phenomena are associated with constant heat production and increasing environmental temperatures. An increase

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* The dog, through "panting" depends largely upon this cooling mechanism for his temperature adjustment.

of air temperature automatically raises the skin temperature to a new level to provide a sufficient skin–air gradient. Increase in wall temperatures has the same effect with regard to the radiation factor. Perspiration is stimulated by either of these when the skin temperature reaches a point at which additional cooling is required.

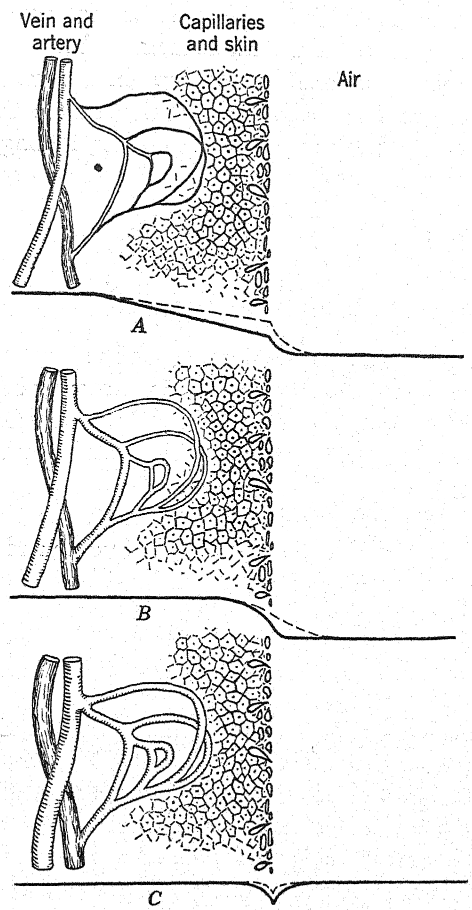

FIG. 9. Thermal gradients through the human skin.
A Cool air; cooling chiefly by conduction–convection.
B Warm air.
C Air at body temperature; cooling wholly by evaporation.
Broken lines, still air.
Solid lines, air in motion.

THE NEW HAVEN STUDIES

PARTITIONAL CALORIMETRY. Professor Winslow and his associates at the J. B. Pierce Laboratory, at Yale University, have developed a technique for the study of the mechanism of body cooling which they have termed *partitional calorimetry*. In a summary of their data * they account for a complete partition of the thermal interchange between the body and its environment, among metabolism M, heat loss due to evaporation E, and heat loss or gain due to conduction–convection, C and to radiation R.

Expressing these relations as a balance, they have

$$M + S = R + C + E$$

The storage term S represents gain or loss of heat by the cooling or warming of the body, respectively; that is, a cooling body is taking heat from storage, and this heat, like that from metabolism, is lost through the right-hand terms. Thus positive storage is a cooling body, and vice versa.

OPERATIVE TEMPERATURE. For the unclothed subject in still air, radiation is proportional to the skin–wall difference and conduction–convection, to the skin–air difference (see pp. 65, 67). These two may conveniently be combined in the relation

$$R + C = k_o(T_s - T_o)$$

The factor k_o is the *environmental factor,* and T_s and T_o the skin and the *operative temperatures,* respectively. The *operative temperature* appears to be a most useful function in the simplification of the heat-loss relations. It is defined as the mean of the air and wall temperatures, weighted according to the respective effectiveness of conduction–convection and of radiation in cooling. It is the air or wall temperature when these two are the same and, with sufficient approximation for our present purposes, the mean of the two when they are unlike and when the air is "still." The *environmental constant* k_o is then merely the corresponding proportionality factor, or heat loss by radiation and conduction–convection per degree of temperature difference between skin and operative temperatures.

Employment of the function T_o and consolidation of the terms

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* A. P. Gagge, L. P. Harrington and C.-E. A. Winslow, *Am. J. Hyg.,* **26**, 84, 1937. This paper has a bibliography of the earlier papers of the series.

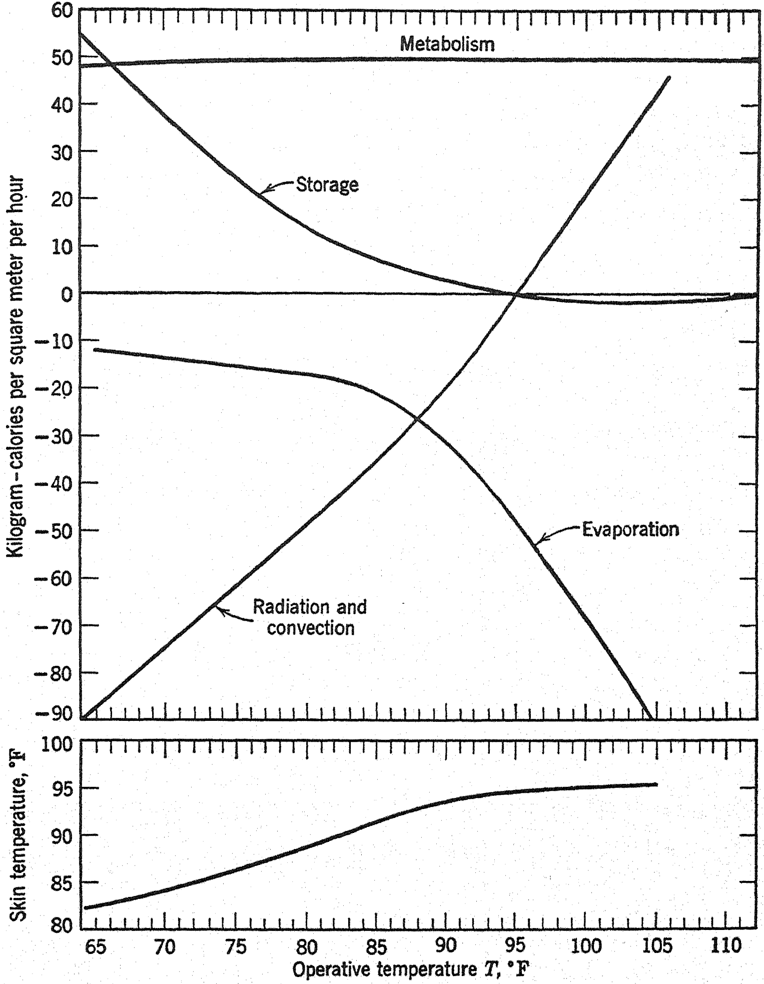

Fig. 10. Rates of heat loss by various channels from the unclothed human body at rest in still air. (The New Haven data)

R and *C* make possible the graphical representation of the terms of the basic partition equation in Figure 10.*

This diagram, as to its numerical values, is applicable to the unclothed semi-reclining male subject at rest in "still" air. It

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* Redrawn in somewhat modified form from the original paper. The corresponding skin temperatures are added at the bottom of the diagram.

illustrates in general, however, the manner in which adjustments are made among the avenues of heat loss under the condition of nearly constant metabolism and variable operative temperature. In the lower-temperature range, the body had not yet come to final equilibrium and was still (after 90 minutes of exposure) subject to lowering bodily temperature.

The skin temperature is the direct and most significant reaction to an environmental change. It mounts steadily with increasing external temperature, but at a lesser rate. In the lower-temperature ranges it maintains perspiration at a minimum, and the chief avenues of heat loss are convection and radiation (negative values in the diagram). At higher temperatures more warm blood is brought to the skin surface, increasing the surface temperature and inducing more active perspiration.

At about 95 degrees, operative temperature, under the conditions of these experiments, the skin has the temperature of the environment; radiation and convection cease, and evaporation assumes control. Above this point radiation and convection become input (positive values in the diagram). Thus, at 100 degrees evaporation amounts to 71 calories and nearly accounts for metabolism, 48 calories, plus the input from radiation and convection, 25 calories. The balance, 2 calories, is going into storage and warming the body which has not yet come to equilibrium.

The Influence of Air Movement. The relations discussed thus far and illustrated in Figure 10, refer to normal quiescent air, the only movement of which is that of thermal currents induced by warm bodies or cool walls. These are generally evaluated, for use in cooling formulas, at about 25 feet per minute. Under the rather confined conditions, during the New Haven experiments, they were found by measurement to be about 17 feet per minute. This is the "still" air condition of Figure 10.

Investigations of the cooling effect of moving air have resulted in rather good general agreement that this effect varies as the square root of the velocity. The New Haven data could be as well expressed by a linear relation, but for conformity the square root relation was adopted, giving

$$C = 0.65\sqrt{v}(T_s - T_a)A$$

where

C = conduction-convection loss, kilogram-calories per hour
V = air movement, feet per minute

A = body area, square meters
T_s = skin temperature, degrees Fahrenheit
T_a = air temperature, degrees Fahrenheit

The constant 0.65 applies, of course, to the specific experimental conditions. For the clothed subject it would have a different value.

THE INFLUENCE OF RELATIVE HUMIDITY. In the region of evaporative control, between the limits of body cooling and body warming, relative humidity modifies the condition of the skin as to its *wetted area* or *percentage of wettedness*. This original concept is based on the following reasoning. From a completely wet surface the rate of evaporation is proportional, among other things, to the saturation deficit in the air (see p. 68). The body surface under most conditions may be considered as a partially wet surface made up of small isolated completely wet areas, surrounded and separated by dry surfaces like lakes and surrounding land.

Under the minimum conditions of insensible perspiration, evaporation from the body may amount to as little as 10 per cent of that which would occur from the completely wet body, or from a free water surface of the same area. If it be assumed that evaporation from the actual wet surfaces is taking place at the normal rate for a water surface at the skin temperature, then only 10 per cent of the total surface of the body is actually wet. This defines the *percentage of wettedness*.

With mounting relative humidity, other conditions remaining the same, the resultant decrease in the rate of evaporation from a water surface is exactly balanced by a physiological response which increases the *wetted area*. Thus, evaporative cooling remains constant, and the thermal balance is unaltered by changes in the relative humidity of the air.

It will undoubtedly appear that this conclusion is at variance with common experience, as expressed in the statement, "It's not the heat; it's the humidity." There is, in fact, a direct relation between higher humidities and *discomfort* in warm weather. This can be traced largely to the effects of clothing. If evaporation of the total perspiration is complete, within any relative humidity range whatever, then cooling by evaporation is uninfluenced by relative humidity within that range, as has been experimentally demonstrated. But at the higher percentages of wettedness, induced by the higher humidities, sticky wet clothing and the resultant interference with air circulation are discomfort factors that enter into the practical consideration.

It follows, of course, that at the *dripping stage* when perspiration is being wasted and does not bring cooling, a lower humidity or more air movement brings relief by an increased rate of evaporative cooling.

Dry Air. In addition to its relation to body cooling, there are certain other aspects of humidity which must be dealt with in the establishment of air standards. These have to do more particularly with low humidities and dry air. They were not included in the New Haven studies but may conveniently be discussed at this time.

As a physical fact, an outdoor air at 32 degrees Fahrenheit and 50 per cent relative humidity, carries 1.06 grains of aqueous vapor per cubic foot. If this air be heated to 70 degrees, at which temperature saturation requires about 8 grains (see Table 9), the relative humidity will be reduced to about 13 per cent. In northern classrooms the heated winter air generally attains a relative humidity of 25 to 30 per cent from the evaporation of perspiration.

Dry air induces more rapid evaporation from the moist membranes of the eyes, nose, and throat, tending to dry out those tissues if evaporation exceeds the supply of fluid. It is a commonly expressed opinion that this condition is conducive to "catching cold," an opinion which does not appear to be based on any satisfactory experimental or statistical evidence. Possibly the inverse relation, that the onset of a cold is frequently accompanied by a sensation of dryness in the throat, has something to do with the common belief. Again, dry air leads to the resuspension of fine dust particles from floors and carpets and to a "dusty" sensation in the throat and sometimes to sneezing, all suggestive of an oncoming cold.

Another suggestion has been that nervous tension and irritability may result from exposure to very dry air, possibly as a reaction to dry membranes. The New York State Ventilation Commission investigated this question in a rather extensive series of experiments. The experimental subjects performed a number of tasks designed to test their neuromuscular reactions and co-ordination. As between relative humidities of 25 and 50 per cent no significant differences were found.

Dry air, like high humidity, probably enters the equation as a comfort factor. In this respect there is probably a wider individual divergence of preferences than in the matter of the most comfortable temperature; it is related to the natural dryness or moistness of the skin. Dry air causes furniture to shrink and loosen at the joints, makes woolen carpets and rugs brittle and friable, leading to dustiness, and permits the accumulation of static electric charges on the body sufficient to cause an unpleasant "shock" when discharged upon contact with a metal doorknob.

CHAPTER 5

HEATING, VENTILATION, AND AIR CONDITIONING

DEFINITIONS

The practical art of controlling the air conditions within enclosed and occupied places is best described under the conventional title of *heating and ventilation.*

Ventilation (Latin, *ventulus,* a little wind or breeze) implies the replacement of the overheated or otherwise modified or vitiated air by a supply of fresh or purer air. It can be adapted to the control of thermal environments and to the maintenance of the concentration of an undesired contaminant below any specified value.

Heating becomes necessary whenever the thermal environment would otherwise permit too great heat loss from the body. In the North, during the so-called heating season, heat losses through windows and walls of a building usually exceed the cooling requirements of the occupants, and heating must be provided.

During hot weather and in the South the opposite condition prevails. The thermal environment is overly warm for adequate cooling of the body. Artificial *cooling* of the air is the latest contribution of the heating and ventilating engineer to the art of air control. Regarded at first as a luxury, it is being improved and cheapened and is gaining ever-increasing popularity. In many industries, its record has been one of increased output and better products; in theaters and stores, of increased patronage; and in the home and office, of growing appreciation and adoption.

Air conditioning is a rather unfortunate expression. Literally, any modification of the air in the direction of greater comfort or of better adaptation to industrial conditions is conditioning. This connotation would include simple heating in the home or humidification in a cotton mill.

Early confusion caused by the loose employment of the term, including its fraudulent use in the overnight type of real estate "developments," led the American Society of Heating and Ventilating Engineers to adopt a standard definition. As thus defined, air conditioning includes the simultaneous control of the temperature, relative humidity, and cleanliness of the air, as well as its volume, distribution, and motion. In its complete form, control of temperature and of humidity includes both warming and cooling, humidification and dehumidification.

PRACTICAL STANDARDS

Standard specifications for the physical properties of air, satisfactory for comfort cooling, can be written only with reference to occupancy. They will depend to a large or even controlling extent on the degree of physical activity of the group and, to some extent also, on the age, sex, and clothing of the individuals, and even on their customs. Very different sets of conditions would be required, for example, in a YMCA gymnasium and in a kindergarten classroom. Similarly, specifications for chemical characteristics—with reference to industrial plants—must be written in terms of specific harmful contaminants and their known physiological effects and limits of tolerance.

A GENERAL SPECIFICATION

It is possible, however, to generalize our total knowledge of environmental air conditions as they affect human welfare, comfort, and efficiency. This has been done most successfully by a Committee of the Industrial Hygiene Section, American Public Health Association in the following form:

Outline of Working Standards

for Atmospheric and Space Environments for the Maintenance of Health, Comfort, and Efficiency

1. Cool rather than hot, but avoiding a sense of chilliness.
2. Dry rather than damp.
3. Still or moving depending upon physical activity.
4. Some diversity in temperature—time and space—rather than uniformity and monotony.
5. Foot level as warm as head level.
6. Radiant, i.e., local, heat source as an item in heating preferred.
7. Shockless temperature differentials between air conditioned quarters and outer air, depending upon the length of stay indoors, i.e., less differential for brief stays.

8. Essentially noiseless conditioning apparatus.
9. Allotments of floor area adapted to individuals and use.
10. Reduction of obnoxious dusts, bacteria, fumes, vapors, and gases to their sub-danger thresholds.
11. Satisfactory primary sense impression upon entering the room or space.
12. Maintenance of comfortable conditions during occupancy (room comfort impression).
13. Sufficient replacement of "foul air" with "fresh air" to meet odor comfort requirements. Entrainment or filtering out of objectionable industrial odors.
14. Intelligent supervision.

These 14 points probably provide the most satisfactory set of general specifications that could be drawn up, covering most of the specific situations that will arise. Adopting them as a point of departure, let us see how far it is possible to go in the direction of specifications for air conditions applicable in practice to particular groups and situations.

TEMPERATURE

Temperature, the most important single variable in the atmospheric environment, has been extensively studied as to its hygienic significance and optimum range in various specific situations.

Classrooms. The New York State Commission on Ventilation, after an extensive study of schoolroom ventilation laid great stress on the value of moderate temperatures and the ill effects of overheating. We may take the grade-school classroom as a typical and well-defined situation. The Commission found that an air temperature not in excess of 68 degrees Fahrenheit represented an optimum condition for comfort and well-being. They concluded:

> Finally it must be emphasized, in closing this discussion that the avoidance of overheating is the primary essential in all systems of ventilation. Air change, direction of flow, and all other factors are secondary. The most important article of ventilating equipment is the thermometer; and, however simple or however complex an apparatus may be installed for air conditioning, a constant and intelligent vigilance in regard to operation and overheating is the price of health and comfort.

With regard to the younger grades, especially the kindergarten grade, it was recognized that a somewhat higher temperature is desirable, perhaps 70 degrees, and that special attention should be given to the prevention of cold floors.

It was recommended also that open-window ventilation be employed as far as practicable. When properly installed, with window deflectors and direct radiation underneath the entire width of the partially open window, this system, as compared with systems relying on mechanical circulation of the air, provided less complete areation and less movement across the room. The resultant reduction in velocity, in turn, permitted lower temperatures (66–67 degrees) with comfort. It contributed noticeably to that desirable diversity in temperature and movement quite generally recognized as preferable to a monotonous uniformity.

This point is brought up here in reference to a *condition* rather than to a *method* of ventilation, but it is worth noting that the more recent developments in the ventilating art, which have largely discounted the other advantages which the open-window system possessed in 1923, have not thus far attempted to produce this recognized advantage of slight variability.

The temperatures recommended here are somewhat relative and have to do in particular with clothing and custom. In England classroom temperatures of 60 to 65 degrees are recommended, and, elsewhere, the success of out-of-doors classrooms for children suffering from lung troubles is recognized. It is undoubtedly economical to dress warmer and maintain lower room temperatures, but there are advantages in the lighter clothing worn by American children, if properly supplemented with heavier outdoor clothing. Less moisture accumulates on the inner layers and there is less shock on leaving the warm room and going out into a cold air.

The distribution of air temperature about the room is important. At best, there will be cool downdrafts along the windows and outside walls, resulting in a stratification of the air into hot-ceiling and cold-floor strata. This condition is made worse by air leakage about windows and doors, especially in windy weather. It may be helped by insulation and weather stripping and by withdrawing the ventilating stream from the wardrobe which is partitioned off from the classroom but open for a height of one foot along its entire bottom length. This arrangement has the added advantage of drying out any damp clothing hung in the wardrobe in stormy weather (see Figure 11). Lateral distribution of the temperature may also become a problem.

OFFICES. Large offices and other workplaces where groups of adults are engaged in moderately active occupations provide another rather general situation. A telephone exchange is a good example. Here a somewhat lower temperature might be thought desirable in view of the occupational activity, but this factor is compensated in large measure, especially among women workers, by the lighter clothing that is worn. Temperatures of 68–70 degrees appear to be preferred. It is perhaps a safe general rule that there should be a minimum of sensible perspiration or dampness of the clothing.

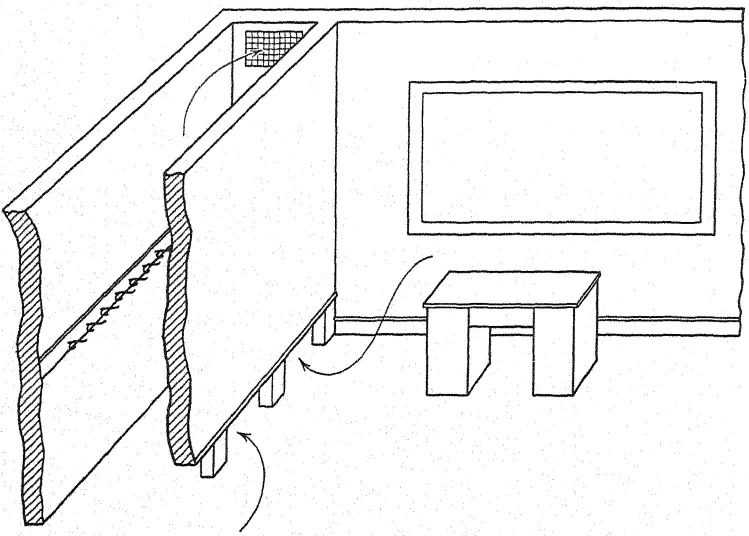

FIG. 11. Preferred system of air exhaust in a classroom.

The optimum temperatures for summer comfort are also found to be relative to the normal outdoor temperature, as well as to age and sex. Some data from representative groups of office workers in several cities are given in Table 13.

AUDITORIA. In places of public gathering, such as the theater, the element of crowding modifies the problem of temperature adjustment. Crowding may run all the way from the densely packed streetcar or subway train to the auditorium where people are seated about as compactly as possible. In all such situations the feeling of body warmth is modified by radiation. As much as 25 per cent of the radiation sphere about the individual may be made up of bodies which neutralize effective radiation to the same extent. A lower air

TABLE 13

OPTIMUM EFFECTIVE TEMPERATURES FOR COMFORT IN OFFICES COOLED IN THE SUMMERTIME

Place	Sex	Effective Temperature Range, 75%	Effective Temperature Maximum
Minneapolis, Minn.	M	68.4–71.3	69.9
San Antonio, Tex.	M	68.8–73.6	71.0
San Antonio, Tex.	F	71.5–74.4	73.0
San Antonio, Tex. (under 40 years)	M & F	69.5–73.5	71.5
San Antonio Tex. (over 40 years)	M & W	70.1–74.3	72.3
Toronto, Canada	M	69.0–70.7	70.0

The *75% range* includes the temperatures at which 75 per cent of the group were "comfortable." The *maximum* values represent the temperatures voted "comfortable" by the *greatest number*. In general, women prefer effective temperatures about 1.1 degree higher than do men; women over 40, about 1.2 degrees higher than women under 40; and men over 40, about 0.8 degree higher than men under 40.

temperature is required to yield an equivalent operative temperature (page 76).

For a lecture, concert, or single theatrical performance, during the winter heating season, it is well to precool the room to 60 degrees. At this temperature the audience will feel comfortably warmed as they arrive after some exertion and clothed for cold weather. The unavoidable rise in air temperature will then compensate for the gradual letdown of bodily activity of the seated audience, and overheating toward the end of the period will be more easily avoided.*

RADIATION. In general, as we have seen in the discussion of operative temperature, the characteristics of the body–wall radiation enter the formula for the room temperature. Radiant heat from such high-temperature sources as an open fireplace, when combined with a cool air, yields a most comfortable sensation. It corresponds to summertime exposure to the sun under cooling ocean breezes. In each situation there is overcooling by conduction–convection balanced by a radiant input.

* This description of auditorium heating comes to memory from the classroom teaching of Professor William T. Sedgwick, "a Pioneer of Public Health." As curator of the Lowell Institute, Sedgwick had the responsibility of planning the series of winter lectures known in Boston for so many years as the "Lowell Lectures" and of engaging and introducing the distinguished personages who participated. It was characteristic of Sedgwick that he also *assumed* the janitorial duties of managing the ventilation of the lecture room, old Huntington Hall in the Rogers Building on Boylston Street. In this capacity he devised, by the experimental process of trial and error, the procedure outlined here.

The opposite effect is unpleasant to the same extent. Nothing is more uncomfortable than cold walls in a warm room, sometimes referred to as "cold seventy." Radiation losses are so great that they cannot be made up from the air by convection, and a deep-seated chill is felt. This was probably one reason for the general use of tapestries in the old stone castles. Any such hanging takes on a temperature approaching that of the air. Radiation interchange is then governed by that temperature rather than by the temperature of the wall.

In the opposite direction, excessive radiation is often a serious problem. In the steel mill, the boiler room of a steam plant, or even the kitchen of a large hotel, radiation is too intense to be balanced by any practicable lowering of the temperature of the room. Skin temperatures must rise to the point of profuse sweating, and reliance must be placed on evaporation and convective heat transfer. The strong air currents needed, in turn, preclude low air temperatures.

In this situation, we find an excellent example of the interdependence of the various cooling principles, as well as of the difficulty of attempting to standardize any one of them.

Air-Cooled Buildings. Artificial air cooling during hot weather presents a problem in temperature control of somewhat different character. There is an unavoidable shock to the individual's heat-regulating system upon entering or leaving a building in which the temperature and humidity conditions differ markedly from those outside. The effect is no different in character and is much less in degree than the corresponding effect of leaving or entering a winter-heated building. In the latter instance, however, it is mitigated by a change in external clothing.

People enter an air-conditioned theater, for example, after having been exposed to the summer heat of a city street combined with the activity of walking or "shopping." Unlike going out from the home in the winter, they do not put on extra clothing, their bodies are wet with perspiration, and they relax instead of increasing their bodily activity. The immediate shock felt on entering the cooler and dryer air is due largely to the increased rate of evaporation during adjustment to the new humidity conditions. This is temporary, but it cools the skin unduly and may lead to sneezing and "catching a cold" on the part of the more susceptible individuals.

The effect on leaving is just the reverse. The cool dry skin is not in position to take up the extra load of intense radiation and greatly reduced conduction–convection loss. The latter may, in fact, become a gain in a city street exposed to hot sun and little breeze. Here the effect of the sudden rush of blood to the peripheral circulation gives a feeling of dizziness, which although again only temporary may be somewhat alarming and ought certainly to be avoided.

These considerations have led to limitations of the cooling differentials between inside and outside which can best be determined experimentally for any given region and climate.

INDUSTRIAL CONDITIONS. Temperature regulation in workplaces, which are characterized by heat production from industrial processes in *excess* of normal room-heating requirements, constitutes another type of problem. It may as well be conceded at the outset that these conditions are not always subject to limitation and control and that uncomfortable and even unhygienic conditions cannot be wholly avoided. We deal here, not with optimum conditions, but with the maximum practical amelioration of unfavorable ones.

We are reassured somewhat by the evident effects of adaptation. Workers do *appear* to be able to withstand conditions that are intolerable to one unaccustomed to them. This is a subject, however, upon which there has been too little scientific study. With increasing consideration being given to the welfare of the human machinery of industry and with growing appreciation of the efficiency factor of labor, as in engines, the *practicable* moves continuously toward the *desirable* if not to the *optimum*. The public-health engineer will find many opportunities in this field for the exercise of his ingenuity and his salesmanship.

In addition to the studies of classroom ventilation carried on by the New York State Commission in the schools themselves, an extensive series of experiments were made under the more adequately controlled conditions of an air-conditioned room. These experiments were planned to develop some of the basic principles, and the data bear on the question of the influence of unfavorable conditions such as are more likely to be encountered in factories than in the classroom. Some of the findings are briefly summarized here.

Three experimental conditions were set up as follows:

	Standard	Hot	Hot–Moist
Temperature, °*F*	68	75	86
Relative Humidity, %	50	50	80

The physical discomfort associated with the hot–moist condition was not accompanied by any change in *mental ability* or *activity,* as measured by the performance of various mental tasks and as compared with the standard condition.

The *inclination* to do mental work was slightly inhibited, as was indicated when subjects were given the option of doing mental work or of merely idling. This effect was not noticed under the hot condition. Under both hot conditions there was a marked and significant decrease in the output of physical work even when stimulated by a cash bonus. As compared with the standard condition, this decrease amounted to 15 per cent at the hot condition and to 28 per cent at the hot–moist condition. This effect was most noticeable during the afternoon hours.

The work output, under bonus stimulus, was measured in a series of experiments designed to measure the effect, if any, of *vitiated air,* that is, air which had been continuously recirculated through the conditioning equipment. Fresh air at the same temperature and humidity was used in the control tests, and in each case the room air was kept in active motion by fans. The only known differences between the two conditions were chemical, oxygen and carbon dioxide and some odor.

The data are given here in Table 14 in relative terms. It is apparent that there was a definite effect which was *not* affected (relatively) by temperature, (77 being 91 per cent of 85).

TABLE 14

EFFECT OF STAGNANT OR VITIATED AIR ON WORK OUTPUT

Relative Values

Temperature, °F	Relative Humidity, %	Fresh Air	Vitiated Air
68	50	100	91
75	50	85	77
86	80	72	..

HUMIDITY

If temperature is the most important single variable in the atmospheric environment, humidity is certainly the most complex. The physiological facts themselves are complicated and have long been misunderstood and misinterpreted. The physical facts suffer from the confusion between relative and absolute humidity with varying temperature.

The latter relations may best be appreciated perhaps by setting up a table of the evaporative capacity of air at various temperatures and at a uniform relative humidity of 50 per cent of saturation. Recalling that *per cent of saturation* is the common basis for evaluating the *dryness* (that is, the drying characteristic) of the air and that the evaporative capacity is represented by the saturation deficit, we see that Table 15 presents the matter in an instructive form.

TABLE 15

EVAPORATIVE CAPACITY OF AIR AT VARIOUS INITIAL TEMPERATURES AND AT 50 PER CENT RELATIVE HUMIDITY AND AFTER BEING HEATED TO 86°

Temperatures in Fahrenheit

Initial Temperature, *T*	Evaporative Capacity, Grains per Cubic Foot	
	Initial	Heated
32	1.1	12.1
50	2.1	11.1
68	3.8	9.4
77	5.0	8.2

The evaporative capacity at the air temperature is merely the saturation deficit, which is 50 per cent of the saturation values given in Table 9. Here the warmer air, always at 50 per cent relative humidity, obviously has the greater drying power. It would dry a wet cloth much more rapidly and with less need for air replacement.

But this air is warmed by contact with the human skin and somewhat cooled by evaporation of the perspiration. For purposes of illustration it may be assumed that the temperature of a thin film of air in equilibrium with the skin surface reaches 86 degrees. The drying capacity of this film is then related to the saturation value at 86 degrees, 13.2. It is, in fact 13.2 minus the initial evaporative capacity. These values are given in the third column of Table 15. It is seen that, under the conditions set up, the initially cooler air is the more drying in the sense that it possesses the greater drying capacity when brought into contact with the skin.

In sedentary occupations and under any conditions below the region of complete evaporative control, the humidity of the air is of minor concern in heat loss. Even at vigorous exercise, it has been seen how the wetted area is automatically varied to provide heat balance independent of humidity. The discomfort factor, discussed earlier, is the controlling feature.

During the heating season low relative humidities result from heating cold air with its naturally low content of aqueous vapor. Here again discomfort factors are mainly involved (p. 80). Artificial humidification is usually applied in air conditioning. Other practices, like the provision of pans of water behind steam radiators, are mostly futile, even if, as rarely happens, they are faithfully attended. At best, artificial humidification cannot be carried beyond the point at which condensation occurs on the windows and cold walls. At outside temperatures of 30 degrees and of zero (Fahrenheit) the inside humidity is limited to about 33 and 13 per cent respectively.

AIR MOVEMENT

Because of its important relation to body cooling, air movement is included as a factor of primary importance in air specifications. The cold downdraft from cool walls and windows is uncomfortable and chilling. It is aggravated by leakage. This effect cannot be overcome or neutralized by the usual expedient of turning up the thermostat. This may even make the drafts more noticeable. Insulation and weather stripping and radiators placed under the more exposed windows are of assistance. The forced and regulated circulation of an air-conditioning system provides the best solution.

During the cooling season—warm weather—gentle currents, preferably induced by withdrawal of the heated air from above, assist body cooling and add to comfort. Too strong or too concentrated air movement, especially if the stream is incoming cooler air, may create undesirable drafts, but this is largely a matter of individual reaction. The control of air distribution and circulation in larger places of assemblage, theaters and auditoria, is one requiring expert knowledge and experience.

QUANTITY OF AIR

The older air specifications, based on a permissible concentration of carbon dioxide as a chemical contaminant, usually called for replacement of the air of classrooms and similar places of gathering at a rate of 30 cubic feet per minute per capita. If we are now to regard ventilation as serving primarily to cool the body, some revision of this standard is evidently in order.

Air movement within the room is desirable, but in any schoolroom in the North, during the winter season, more than adequate cooling of the air itself is obtained by convection losses through the walls. Artificial heating must be resorted to, in addition to the body heat of the occupants, to maintain a comfortable temperature.

RECIRCULATION. Some recognition of these facts is seen in the current practices of recirculation of the air; providing movement and local heat removal about the individual and carrying this heat to the walls for cooling. By the employment of this principle the requirements for fresh air and the cost of heating unnecessarily large volumes of cold air have been greatly reduced. In the end, however, the accumulation of body odors and of a general mustiness that survives even washing of the recirculated air puts a limit to this economical process. The amount of fresh air required depends to a considerable extent on the personal hygiene of the group as regards bathing, bad teeth, and the like, but, in general, it is not less than 10 cubic feet per minute per capita. In practice, the older standard quantity of 30 cubic feet is generally recirculated, about one third of it being replaced continuously with fresh air.

AIR QUALITY

Obviously, then, we cannot rest wholly on the comfortable doctrine that ventilation means merely physical cooling under conditions adapted to human physiology. Whereas the early views of chemical vitiation of the air, as measured in terms of carbon dioxide, have had to be abandoned, air quality still has significance in practical air standards.

RE-USED OR VITIATED AIR. Reference has been made (p. 90) to an apparent effect of re-used air on the work output. A further and rather definite effect on the appetite was demonstrated during the investigations of the New York State Commission. Experiments were carried on with small groups of four to eight subjects. Each group was exposed on alternate days, over periods of 12 to 20 days, first to fresh air and then to air which was continuously recirculated throughout the morning hours, and hence constantly rebreathed. The test applied was the caloric value of the food eaten at lunchtime when more than adequate servings were placed before each of the subjects. The data are summarized in Table 16.

TABLE 16

APPARENT EFFECT OF VITIATED AIR ON APPETITE
(New York State Ventilation Commission Data)

Number of Subjects	Days	Excess Calories Taken on "Fresh-Air Days," Per Cent
4	18	13.6
4	20	8.6
7	28	4.4
8	20	6.8
Weighted Average		6.0

The indication was somewhat confirmed by the demonstration that strong organic odors (fecal) produced a transient but definite check on the growth of guinea pigs. The Commission concluded that, whereas thermal conditions play a major role, it cannot be denied that there is a subtle effect, possibly due to odor, on the sensitive function of appetite.

Similar effects have been noted by various investigators in the reactions of sensitive individuals, more frequently among the elderly and infirm, to atmospheric odors of industrial origin (see chap. 8). Perhaps it is not far amiss to note here also the bracing and invigorating effects of the odors of the seashore and of the pine woods.

These are not matters that lend themselves to quantitative standardization, at least with our present inadequate data. But they are matters that cannot be overlooked in considering air standards. Present practice leans toward controlling the *freshness* of the air merely by regulating the volume of fresh air introduced during recirculation.

BACTERIAL IMPURITIES. The significance of bacterial contamination has been sufficiently discussed (p. 31). Here again, although the primary facts are well proved, quantitative data are lacking for the establishment of standards of permissible contamination. The outlook is promising, however. It is not too much to expect that standards of air quality, based on the quantitative presence of some common normal inhabitant of the nose and throat, will be set up to measure conditions of relative purity of the air, just as has been done in the parallel case of water standards based on the intestinal organism, *E. coli*.

INDUSTRIAL CONTAMINATION. One is confronted with a difficulty of the opposite sort in the matter of industrial contaminations. These have been so extensively studied, and the resulting data are so voluminous, that any attempt to summarize them in a useful way and within reasonable space limitations is impossible. Reference may be made to the standard works cited at the end of this chapter. It will be sufficient to note that the necessary and sufficient procedure in each specific instance is a physiological investigation of the limits of tolerance to each such impurity and specification of standards of permissible concentrations, taking into consideration whenever appropriate, the necessary or usual periods of contact (see p. 5).

Miscellaneous Impurities. Air cleansing is one of the features of modern air conditioning, and air standards of the future will contain specifications limiting the concentration of smoke, soot, and ordinary air-borne city dirt to such minima as are found practicable. One of the claims made for certain household equipment is that it will eliminate the ragweed and other plant pollens which cause so much distress among those susceptible to attacks of *rose fever, hay fever,* and similar allergic reactions.

VENTILATION PRACTICE

The practical art of heating, ventilation, and air conditioning has, for many years, been far in advance of our scientific knowledge of the biological facts and factors on which the whole matter eventually rests. That is to say, the engineer has long been prepared to heat, cool, dry, moisten, and cleanse the air and circulate it through the building in accordance with any specifications that may have been prepared. On the other hand, the physiologists and the hygienists have responded with tentative, diverse, and often conflicting opinions regarding specifications for an optimum atmospheric and thermal environment.

This condition reflects the respective difficulties and complexities of the two aspects of the problem, the mechanical and the physiological, rather than any inherent differences between groups of scientists. The physical sciences are the more "exact"; their basic laws, the better understood. The result of doing a certain thing in a certain way can be rather accurately foretold. Conversely, the mechanical means by which a given end can best be attained can be blueprinted, after preliminary study of principles, with reasonable assurance.

Having reviewed in some detail the physiological aspects of our problem, we may now best serve our present purpose, a study of principles, if we outline briefly, and in a purely descriptive manner, the methods that are currently employed in the practice of ventilation without undertaking to study mechanical equipment in any detail. On the more strictly engineering phases of the subject there is adequate literature. In particular, the *Guide,* annual publication of the American Society of Heating and Ventilating Engineers, will be found complete, authoritative, and up-to-date.

VENTILATION BY DILUTION

THE DISPLACEMENT CONCEPT. Ventilation or blowing through is commonly thought of as merely a process of replacement. This is expressed by the terms *replacement time* or *air changes per hour.* It represents streamline flow as illustrated in Figure 12*A*. Here the stream of air is seen entering in parallel streamlines, each new increment maintaining an unbroken front, like a rank of soldiers. Suppose the room has a total volume, V, of 10,500 cubic feet, and the ventilating stream, a flow, Q, of 5250 cubic feet per minute. Then the *displacement time* or the time required to fill the room if it were initially empty is 2 minutes; in general, V/Q.

If the flow could be made strictly streamline, then every particle of air entering the room would leave just 2 minutes later, and it could be said that the air of the room is completely replaced, that is, renewed, every 2 minutes. This situation, however, never exists.

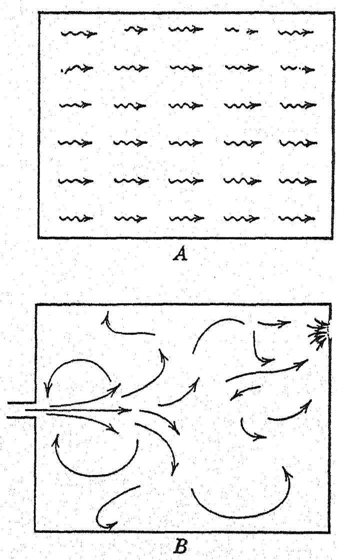

FIG. 12. *A* Ventilation by displacement. *B* Ventilation by dilution.

THE DILUTION CONCEPT. The actual situation is better represented in Figure 12*B*. Air is extremely mobile. It is set in motion by the very least difference in pressure or density (temperature), and the movement of any portion is rapidly conveyed to adjoining portions. The entering stream has a considerable velocity which carries it forward well into the room. Adjacent layers are sucked backward toward and into the entering stream, thus diluting it and reducing its velocity. Other convection currents abound wherever there are temperature differences: downward along cool walls and windows, upward from all warm surfaces including human bodies.

The result is such a complete degree of mixing that it is much nearer to the true picture to assume that the air within the room is completely mixed at all times. This leads to the concept of *ventilation by dilution*. Under this concept it is assumed that any given small volume of incoming air, the *tracer volume,* is instantly and uniformly mixed with the air of the room. Under the room-volume and flow relations previously assumed, one half of the total air volume, and consequently one half of the tracer volume, is removed during the next minute. During the following minute, one half of the remainder of the tracer volume or one fourth of the original quantity is removed, and so on continuously.

Thus the tracer volume, instead of passing through the room in 2 minutes, as it would under the assumption of uniform replacement, has a period of sojourn in the room represented by

$$F = 0.5^t$$

F being the fraction of any incoming portion of air remaining after t minutes. If it be noted that the value 0.5 was derived from the basic values, room volume V and rate of ventilation Q, by the relation,

$$1 - \frac{Q}{V}$$

then the dilution formula can be generalized as

$$F = \left(1 - \frac{Q}{V}\right)^t$$

This represents the fate of any specified tracer volume, such as any single influx of an atmospheric contaminant. Under the dilution concept of ventilation its concentration would diminish continuously, but it would never entirely disappear. This concept, too, is somewhat ideal, but it approximates the truth and provides a satisfactory basis for the computation of ventilation volumes and room conditions.

An Illustrative Case. By way of a simple illustration, let us consider a room into which there is a constant flow of fresh air and another constant flow of some contaminant a class of school children. It is permissible under the dilution concept to represent the room conditions as in Figure 12*B*. Let air be exhausted from the room at a rate of Q, and let q represent the rate of inflow of the contaminant in the same volumetric unit. The contaminant stream q is immediately diluted into the entire room volume, and some of it leaves at once through the exhaust. That portion which leaves is less than the incoming stream, so that the concentration of contaminant in the room builds up continuously. The rate at which this accumulation takes place is discussed under *room volume.*

When the concentration of the contaminant in the room air, expressed in volumetric per cent, becomes equal to the ratio of the two stream flows,

$$\frac{q}{Q}$$

then the out-flowing stream Q will carry a stream of contaminant,

$$Q \times \frac{q}{Q} = q$$

Equilibrium has now been reached. The concentration of the contaminant in the room air will remain constant and equal to its concentration in the exhaust stream; this will be the volumetric ratio of inflow of contaminant to total flow of air or

$$\frac{q}{Q}$$

AN INDUSTRIAL PROBLEM. This formulation may now be applied to an industrial condition. A lacquer, dissolved in toluole is being used in a room at such a rate that one gallon of the solvent is evaporated in the room air each hour. If the permissible limit of concentration of toluole in the air of workrooms is 100 parts per million what is the required ventilation rate?

The volume of toluole vapor produced per hour must first be determined. A useful formula of sufficient accuracy for this purpose is

$$\text{Cu ft of vapor} = 416 \times \text{pints of solvent} \times \frac{\text{specific gravity}}{\text{molecular weight}}$$

The specific gravity of toluole is 0.872, and its molecular weight, 92. Substituting these values gives 3.94 cubic feet of vapor per pint of fluid, or at a rate of consumption of one gallon per hour, 31.5 cubic feet per hour. Now substituting, we get

$$\frac{q}{Q} = \frac{31.5}{Q} = \frac{100}{1{,}000{,}000}\,; \qquad Q = 315{,}000 \text{ cu ft per hour}$$
$$= 5250 \text{ cu ft per minute}$$

The required ventilation is in excess of 5250 cubic feet per minute by whatever ratio it is concluded that the efficiency of distribution within the room falls below 100 per cent.

A chemical contaminant has been employed to illustrate the principle involved here, but it applies equally to heated or moist air due to human occupancy. This is the basis of ventilation of occupied places. With no heat lost through the walls, cool dry air would be employed to replace the warm moist air being continuously produced. During the heating season extraneous losses of heat generally exceed the heat production by occupants, and the ventilating stream is heated accordingly. Heating the outside cold air may reduce its relative humidity to a point where the rate of production of moisture by the occupants is less than sufficient to maintain the desired value. Here the rule, working in reverse, would call for reducing the air stream, but, since its volume is fixed by other considerations, reducing the concentration of odors or of bacteria, the air stream itself is artificially humidified.

During the cooling season heat may be regarded as the contaminant which is diluted out in a ventilating stream of precooled air. Cooling the air increases its relative humidity so that, for proper dilution of the waste humidity from the occupants, more air or dryer air is required. The air volume being fixed by the cooling requirements, dehumidification is applied.

ROOM VOLUME

Specifications for living quarters generally call for a certain space allotment in cubic feet per capita. Yet, it was unnecessary to take room volume into account in the foregoing discussion of dilution ratio. Obviously, when a condition of equilibrium has been reached, at which the rate of removal of any contaminant is just equal to its rate of production, the concentration within the room is fixed by the dilution ratio alone and is independent of room volume. This proposition is important.

RATE OF BUILD-UP. However, there is a period of time following occupancy after nonoccupancy, or after the beginning of the day's work with an industrial contaminant, during which the concentration builds up toward the ultimate ratio, q/Q. The rate of this build-up is a function of the room volume. Its evaluation will require resorting to some simple calculus, but the result will be found of sufficient interest to justify the effort.

Let

$V =$ room volume
$Q =$ ventilation rate
$q =$ rate of production of contaminant
$t =$ time from the start
$C =$ *amount* of contaminant in the room

Then

$$\frac{V}{Q} = \text{time required for one air change,}$$

$$= \text{displacement time, } T$$

and

$$\frac{C}{V} = \text{concentration of contaminant in the room}$$

all dimensions being consistent, say cubic feet, minutes, and cubic feet per minute.

At any time t the amount of contaminant in the room C is being augmented at a rate q and being reduced by withdrawal of air, rate Q, having a concentration of contaminant C/V or at an over-all rate of

$$\frac{QC}{V} = \frac{C}{T}$$

Thus we may write for the net rate of change,

$$\frac{dC}{dt} = q - \frac{C}{T}$$

which integrates to

$$\frac{C}{V} = \frac{q}{Q}\left(1 - e^{-\frac{t}{T}}\right)$$

The function in parenthesis is the ratio between the concentration C/V at any time t and the ultimate or equilibrium value of the concentration q/Q. For more convenient solution we express this ratio as P, per cent of ultimate concentration, and transform to the logarithmic relation,

$$2.3 \log \frac{100}{100 - P} = \frac{t}{T}$$

Solution of this expression at a few points will indicate the trend of the concentration toward equilibrium and the influence of room volume.

Time in Terms of Displacement Time, t/T	Concentration in Terms of Ultimate Concentration, P, Per Cent
0.1	9
0.3	26
0.5	39
0.7	50
1.0	63
1.5	78
2.0	87
3.0	95
4.0	98

ROOM VOLUME IN SLEEPING QUARTERS. The significance of these relations can best be illustrated by reference to such conditions as are to be found in Army barracks or on shipboard. In Table 17 we have set up four hypothetical situations, representing barracks in which ventilation requirements are met by forced or mechanical ventilation.

TABLE 17

ROOM VOLUME AND VENTILATION RATES

Condition	Room Volume, V	Ventilation Rate, Q	Displacement Time, T	Contamination			
				Rate, q	Ultimate, q/Q	30 Min	1 Hr
A	8,600	430	20	40	0.093	0.073	0.089
B	17,200	430	40	40	0.093	0.049	0.073
C	8,600	430	20	20	0.047	0.036	0.044
D	8,600	860	10	40	0.047	0.044	0.047

The contamination rate q may represent men. If so the ultimate value q/Q is the reciprocal of the ventilation rate expressed in cubic feet per capita per minute, other volumes being in cubic feet and rates in minutes.

Condition *A* represents definite overcrowding, about 27 square feet and 215 cubic feet per capita (with 8-foot ceiling). In an attempt to relieve this situation a second barracks is built with ceiling height doubled (condition *B*). The floor space remains the same, and, with the same rate of ventilation, the ultimate contamination will be the same. The single advantage of this change is seen however in the somewhat slower approach to the ultimate concentration. On the basis of an 8-hour night the improvement hardly appears worth while, being confined primarily to the first hour.

If the number of occupants be reduced to 20 (condition *C*) and the same volume per capita be provided as in the previous case *B* but double the floor area, the ultimate contamination and all intermediate values are reduced one half. This is clearly an improvement over condition *B* but somewhat more expensive since it doubles the floor area required for a company.

Finally, in condition *D,* we return to the full occupancy (40) but double the ventilation rate. This achieves the same ultimate concentration of contamination as does condition *C,* reached only slightly more rapidly. The ventilation, in cubic feet per capita, is the same in the two cases. Within certain limitations this change appears, on the whole, to be the most advantageous.

The limitations are obvious. Ventilation rates cannot be increased indefinitely. The higher ceiling provides a greater cross-sectional area through which a given air flow passes with less linear velocity. This may or may not be desirable according to other circumstances. High ceilings also provide space for the accumulation and gradual cooling of the rising current of warm air. This advantage, however, can be had equally from suitable roof ventilators.

Finally, the illustration is based on the employment of forced ventilation of known and constant rate. Under the circumstances of ventilation by natural means through windows and roof ventilators, the assumed conditions are approximated, but air movement now depends somewhat on the "chimney action" of the heated air column within the building. The higher this column, that is, the higher the ceiling, the greater the rate of air circulation.

This rule works to the advantage of the small home in severe winter weather. The "snugness" of the low-ceilinged New England farmhouse is in marked contrast to the "draftiness" of the high-studded mansion. The high ceilings provide a greater temperature differential for the establishment of vertical circulation—downward along the cold walls and upward in the center of the room—and for the escape of hot air through the ceiling and upper window openings and the resultant indrawing of cold air at the lower levels.

NATURAL VENTILATION

A *system of ventilation* may be defined as any combination of means for supplying fresh air and heating the air or the space, together with any such auxiliary operations as cleansing, recirculation, cooling, and humidity control. There are various separate means for accomplishing each of these purposes so that the number of possible combinations is large. They may be described, however, under a few of the combinations more frequently employed.

The extreme mobility of air, its ability to pass through small openings under slight pressure, its tendency to rise when only slightly heated and the general movement of outdoor air as wind all contribute to the operation of *natural ventilation*. By utilizing these physical properties it is possible to secure adequate ventilation of the home, office, or small classroom through partially open windows or even by normal leakage. Circulation is enhanced by the installation of *gravity-exhaust ducts* leading to a point above the roof. These provide a chimney action due to the difference between inside and outside temperatures. If equipped with a suitable cowl, they make use of the wind movement to produce suction in the flue.

The New York State Commission found natural ventilation with gravity exhaust entirely adequate to provide satisfactory room conditions in classrooms of New York City schools. The most favorable conditions were found to be:

> Radiation, equipped for hand control, located beneath the windows that are to be used for ventilation and extending the full width of the window.
>
> A wind deflector, preferably of glass, placed in the window opening at such an angle as to direct the incoming air upward and into the convection current rising from the radiator. The window opening is adjusted according to wind conditions so that the incoming stream does not quite blow across the rising stream of hot air and into the room.
>
> A gravity exhaust duct from a point near the ceiling and opposite the windows to the roof, equipped with an efficient cowl.
>
> A large thermometer, prominently displayed; with 68 degrees emphasized, classroom not overcrowded (actually 250 cubic feet per child, second grade, to 310 cubic feet, sixth grade).

When compared with the mechanical systems of that period (about 1920), natural ventilation provided better individual control of conditions in each room and permitted a lower and, it was believed, a more hygienic temperature, owing to the more limited and controlled air movement. It also produced a slight and pleasant variability in both temperature and movement, due to the continuous fluctuations of the wind movement. Open windows, however, were objectionable from the point of view of street noises and wind-blown dirt.

MECHANICAL VENTILATION

The limitations of natural ventilation become more manifest with increasing size of establishment. The high-school auditorium or gymnasium, for example, requires special ventilating features. In larger halls the problem of distribution of a sufficient quantity of air without undesirable local drafts or too great temperature differentials becomes more difficult. Finally, as the specifications for room conditions have become more exacting and have been elaborated to include cooling, cleansing, and moisture control, the adoption of central systems with mechanically forced circulation through the building have assumed increasing prominence in the ventilation field. Generically these are *mechanical systems*.

UNIT-TYPE EQUIPMENT. The small individual room unit of the cabinet type which is becoming increasingly popular, is intermediate between the natural ventilation and the central mechanical systems. Mechanically operated, it combines most of the advantages of the open window with the better control that comes with forced circulation. In particular, it provides some measure of cleansing (cloth filtration), with controlled heating and humidification. The more elaborate cabinet units are complete, with cooling and dehumidification.

AIR CONDITIONING

In the discussion of standards and specifications, *room conditions,* temperature, humidity, movement and cleanliness were stressed as against the older concept of frequency of replacement or other means of attaining the desired end. The most obvious requirement in the tempering or conditioning of the air is that it shall be heated whenever the outdoor temperature is too low for indoor comfort. Thus, at an early stage, *heating* was joined with *ventilation* in such equipment as the hot-air furnace. This intimate relation of the two arts has remained, as is indicated in the name of the national organization, the American Society of Heating and Ventilating Engineers.

HEATING SYSTEMS. Although an entirely distinct function, heating is so closely and so conveniently associated with ventilation that any discussion of ventilation must of necessity deal with heating. Heating of homes, by the fireplace, stove, or radiator, is done without reference to ventilation and requires little comment.

In its study of the rural (one-and two-room) schools of a northern county, the New York State Commission found enormous temperature differences between floor and ceiling levels and laterally across the room. The latter effect was due to direct radiation. A metal jacket surrounding the stove, open at the bottom, helped remedy both these defects. It induced greater vertical circulation by withdrawing cold air from the floor, and it screened off the intense radiation to which those nearest the stove were exposed. The better design of stoves now available for home heating provides this jacket effect in a cabinet of artistic appearance and greatly improved heating efficiency.

Heating by stoves or radiators is *direct heating*. It is employed where natural ventilation is sufficient and, as *split heating,* to take up part of the heating load in mechanical systems of ventilation, the remainder of the load being carried by *indirect* or *central heating*. The hot-air furnace is the original type of indirect heating.

The obvious dryness of the winter air which had been passed through the furnace flues gave rise to another attempt at conditioning and the introduction of the waterpot for humidification. The shortcomings of the early furnaces in the matter of leaky flues and resultant contamination of the air with smoke, soot, and carbon monoxide were possibly responsible for later improvements in the direction of air cleansing. The too frequent occurrence of cold downdrafts in some of the flues supposed to carry hot air upward probably suggested forced circulation.

Whatever its genesis, air conditioning, as we have previously defined it (the simultaneous control of temperature, humidity, and movement with incidental control of distribution and cleanliness), is merely the modern version of the hot-air furnace minus its many shortcomings and plus means for hot-weather, as well as for cold-weather, control. The operation of a complete system can be best described by reference to the diagrammatic sketch in Figure 13.

THE AIR WASHER. From the point of view of the theory of operation the heart of the plant is the air washer. Within this enlarged section of the circulatory system the air comes into intimate contact with water in the form of fine spray. Recalling the definition of the wet-bulb temperature (p. 42) we can see that, if the water is neither heated nor cooled externally, and the air leaves the washer saturated, both air and water will approach the air's wet-bulb temperature. This is known as evaporative cooling.

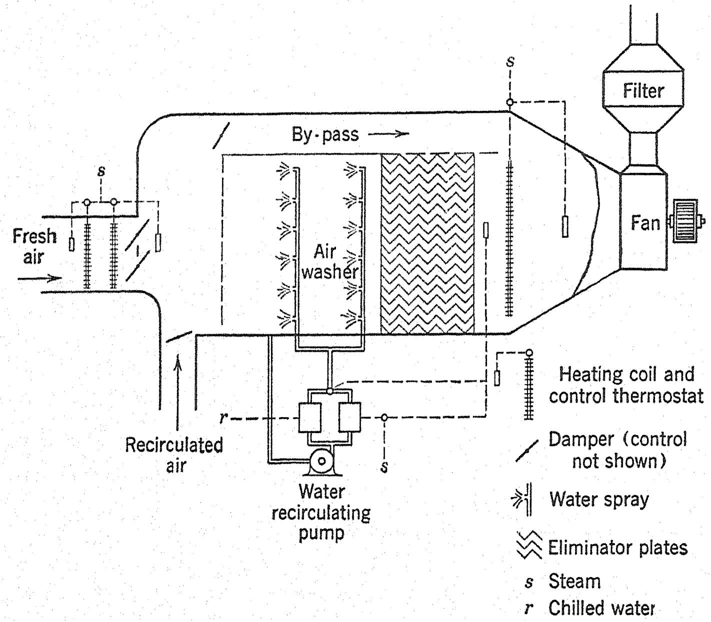

FIG. 13. Diagrammatic sketch of complete air-conditioning equipment.

If the water which is continuously circulated through the sprays is cooled externally, the air temperature tends to approach that of the water and its humidity that of saturated air at the water temperature. If the water temperature is maintained above the dew-point temperature of the entering air (p. 43), the air will be moistened; if below the dew point, moisture will be deposited just as it is deposited on the outside of a glass of ice water.

If the water is continuously warmed externally, the air will be warmed and humidified. Circulation through the washer may be at such a rate that saturation is not complete, but for simplicity it will be assumed that the air leaves the washer at the water temperature and saturated. Thus the temperature of the water controls the *absolute humidity* of the air and, hence, after subsequent heating, its *relative humidity*.

CONDITIONING DURING THE HEATING SEASON. Let us now follow the air stream through this operation during the heating season. The incoming air may have a temperature of 25 degrees. As it is drawn into the system by the fan it passes over a tempering coil controlled thermostatically by the outside temperature. This preliminary tempering merely smooths the subsequent operations by neutralizing extreme variations. The air is further heated by a second coil controlled by the air temperature in the mixing chamber, into which it next passes. Here it joins the flow of return air from the building (recirculation). The relative amounts of fresh and return air are determined, within limits, by the dampers in the respective lines which, in turn, are controlled thermostatically to meet best the required conditions. The by-pass damper is normally closed at this time.

The mixed air, which may now be at about 35 degrees, passes into and through the air washer and humidifier. Here it acquires the temperature of the water and is saturated at that temperature. Humidity control is therefore based on the control of the water temperature at this point. The water is heated externally in a manner to be described later. Within the washer the air is freed from most of its coarser and heavier suspended matter.

An essential part of the washer is the system of eliminator plates, a set of baffles so arranged that the air passes in a zigzag path between rather closely spaced plates. The heavier particles of mist and moistened dirt are unable to make the sharp turns and impinge on the plates where they are held in a film of water.

Leaving the eliminator, the air flows past the dew-point thermostat which, in turn, controls the steam supply to the washer water as it is continuously circulated through the spray system. The temperature at which this thermostat is set determines the final (relative) humidity of the air. For example, air at 70 degrees and 34 per cent relative humidity has a dew point of 40 degrees. This then must be its temperature as it leaves the washer saturated. Hence, the water temperature is maintained by the dew-point thermostat at about 40 degrees—actually a degree or two higher in winter and lower in summer.

The air next passes across the reheater coils where its temperature is brought up to the required point for final distribution, the steam supply to these coils being controlled by a thermostat just beyond. In larger installations the system may be *zoned* with individual *booster* heaters for each zone controlled by thermostats in the rooms.

CONDITIONING DURING THE COOLING SEASON. During the cooling season all steam is cut off. Refrigeration is supplied to the washer water, the temperature of which is maintained by the dew-point thermostat as previously. Now, however, the thermostat operates to by-pass water around the refrigerating system to maintain the desired water temperature. The final air temperature is controlled by a thermostat which operates the large by-pass damper around the washer, mixing warm air with the cooled air from the washer. A maximum of recirculation is employed, and the dewpoint of the cooled air is adjusted to compensate for the extra moisture of the by-passed air.

AIR CLEANSING. Before the air is ready for final distribution, it is generally given a final cleansing treatment. A considerable portion of the heavier suspended matter is removed in the washer; the quality of the wash water, after it has been in continuous use for some time, is ample evidence of this fact. Some attention must be given to this matter, for the development of organic growths in the wash water will give rise to stale and musty odors in the air. Moreover, it has been found that bacteria in the wash water may be resuspended in the air during spraying. City air, in particular, is likely to be laden with smoke and soot and can be much improved by further cleansing by filtration.

In filters of the *viscous* type the air passes through a relatively coarse-grained material coated with an adhesive or viscous fluid. The dust particles are removed by numerous impingements on these sticky surfaces, rather than by any true filtration. Some of the filter media are sufficiently cheap to be discarded after use. Other filters make use of more permanent material which is periodically cleaned. The viscous fluid may be recirculated, gathering the dirt during its descent along or through the filter material, and cleansed by filtration after each passage.

The *dry filters* are of close-grained felt, cloth, or paper, through which the air is forced. The more permanent materials are cleaned by vacuum treatment; others are discarded after sufficient use.

Among recent developments is a device by which the suspended impurities are first given an electrostatic charge and then passed through a strong electric field between two charged condenser plates. The charged particles move toward the appropriate plate, where they are collected and held.

Respirators, which are actually individual protective apparatus, may be classified as air cleansing equipment. Their function is to protect the wearer by filtering out or otherwise removing or neutralizing an undesirable contaminant. A common example is the apparatus worn by workers in dusty occupations. The air is filtered through fine gauze or cloth which removes the dust mechanically. The various types of *gas masks* employed in chemical warfare contain absorbent material such as special charcoals for the physical adsorption of gases, or are provided with chemical reagents for their neutralization. Respirators can be made highly efficient, and their use in certain situations is essential. The chief drawback to such use is the general objection of the worker to the physical encumbrance and inconvenience, so that, except under immediate supervision, he is prone to discard his respirator or affix it loosely for easier breathing.

THE DISINFECTION OF AIR

It has been found experimentally that the ordinary methods of air cleansing, washing, and filtration, although effective on the larger particles of bacteria-laden dust, become less so with decreasing particle size. From an epidemiological standpoint, therefore, they cannot be regarded as of material significance. In addition to this natural limitation of the mechanical equipment, the process of recirculation and intermittent cleansing itself is limited to a certain maximum effectiveness determined wholly by the rate of recirculation.

In the discussion of the dilution concept of ventilation it was seen that the composition of the room air is approximately that of the exhaust air and is numerically the ratio q/Q or rate of input of any specified contaminant to ventilation rate. If the displacement time, at the existing rate of ventilation, is 10 minutes, then the room air will contain at all times a 10-minute input of bacteria from the occupants in addition to any contribution from the accumulated residue that has passed the conditioning equipment during recirculation. Air disinfection deals with this irreducible minimum, which would be present even if sterile air were used in ventilation.

Ultraviolet Light. The powerful bactericidal property of ultraviolet light has long been known. It has been put to practical use in the disinfection of water and elsewhere. It has also been found to be effective against bacteria suspended in air. The earlier studies* indicating the practical possibilities of air disinfection have been followed by an extensive development of the art. The success of many controlled experiments on a practical scale, coupled with the interest manifested by the lamp manufacturers in the development of improved and more efficient units has resulted in numerous installations of the process in children's hospitals, nursing homes, and operating rooms, as well as in such commercial applications as the prevention of mold growths in cold-storage rooms.

One rather serious limitation is the unfavorable affect of the ultraviolet light on the eyes. Common glass is opaque to the rays, however, and provides an excellent protection. For general use the lamps must be concealed so as to be out of sight of the room occupants. Another disadvantage, the production of ozone in unpleasant and possibly harmful concentration in the near vicinity of the lamp, has been largely overcome in the more recent lamp developments. The maximum bactericidal effects reside in rays having a wave length of about 2537 angstroms, whereas ozone is produced by wave lengths shorter than about 2000 angstroms. Lamps are now available which expend some 85 per cent of their energy in the production of light within the maximum germicidal range.

Germicidal Aerosols. *Fumigation* with such gaseous germicides as formaldehyde and sulphur dioxide and disinfection with liquid sprays of carbolic acid have both been employed in the past, only to be abandoned later as ineffective or unnecessary. Today both these techniques are under investigation as promising methods for the disinfection of air.

The earlier studies of the so-called *aerosols* indicated that the effectiveness of such preparations as a solution of hexylresorcinol in propylene glycol depended on actual liquid contact between the bacteria and the solution, dispersed as a spray in particles of less than one micron in diameter.† More recently it appears that the vapors of propylene, ethylene and triethylene glycols, among others, are effective in the gaseous phase.‡

* W. F. Wells and G. M. Fair, *Science* **82**, 280, 1935.

† C. C. Twort, et al., *J. Hyg.*, **40**, 253, 1940.

‡ C. H. Robertson et al., *Science*, **93**, 213, 1941.
M. Hamburger et al., *J. Infectious Diseases*, **76**, 208, 1945.

A great deal of experimental work has been done with aerosols as a war measure, the results of which await publication. Preliminary reports of studies in barracks have shown the relative importance of resuspended dust particles as bacteria carriers and the advantages of oiling the floors and even the bedding. The following data are significant. The bedding was very lightly oiled, and comparative examinations of the room air were made in barracks with treated and untreated bedding and during periods of quiescence as well as during the bed-making period.*

Bedding	Bacteria per Cubic Foot			
	Quiescent Period		During Bed Making	
	Total	Haemolytic Streptococcus	Total	Haemolytic Streptococcus
Untreated	118	6	938	24
Oiled	75	0	276	4

It is safe to predict that rapid advances will be made in the practice of air disinfection. As a feature in environmental control, a barrier between the infectious individual and a possible new victim, disinfection of air is the logical complement of water disinfection and the pasteurization of milk.

EXHAUST VENTILATION

In many industrial operations it is advantageous to prevent the escape of air contaminants into the general circulation. In particular, this permits the employment of lesser air volumes for purposes of dilution. It is also highly desirable in such operations as stonecutting and woodworking where a relatively heavy dust is concentrated locally, affecting the immediate worker but not passing to any extent into the general air of the room. Such dusts are not particularly affected by mere dilution. The immediate removal of a concentrated contaminant at its source is known as *exhaust ventilation*. The common laboratory hood is a familiar example and has, in fact, many useful applications in industrial operations.

In some situation, such as the spray painting of automobiles, the job may be completely enclosed within a small room, ventilated by

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* C. H. Robertson et al., *J. Am. Med. Assoc.*, 126, 993, 1944.

See also a report by the staff, U. S. Med. Research Unit 1, on methods of impregnating textiles with germicidal oils, *Science,* **104,** 60, 1946.

an exhaust system which carries the volatile solvent away from the worker. Other operations can be carried out in partially enclosed hoods while still others cannot be enclosed and must be protected by hooded canopies or other special devices.

REQUIRED VELOCITIES. A first principle in exhaust ventilation is that a *control velocity* must be set up in the area throughout which the contaminant is released or to which it may escape. It is generally assumed that extraneous air currents of the order of 35 feet per minute exist by reason of thermal convection and the movement of machinery and operatives. These must be discounted before the draft created by the exhaust system can become effective. Gases and vapors can, in general, be controlled by air velocities of this order, or, say, up to 50 feet per minute. It must be noted however that if the gaseous substances are hot they tend to rise and that many vapors are much heavier than air and tend to fall. The location of the exhaust grill must be governed largely by these considerations: a canopy over a heated tank or a downdraft grill in the workbench.

To lift and suspend a solid particle, the pressure due to air velocity acting on the surface must equal the weight of the particle. Thus there is a *transport velocity* for each class of material according to its size and density. Transport velocities, in feet per minute, which will just suspend a few typical classes of material are:

Powders, lint, grain dust	2500
Dry sawdust	3000
Sand blast, stone dust	4000
Lead dust, sawdust from green wood	5000

These are the air velocities that must be maintained within the duct system, particularly in rising sections. As far as possible the inlet hoods and enclosures are so placed that the particles *fall* rather than rise with the air current. In grinding and similar operations the enclosure can often be placed so that the particles are *projected* into it.

DISTRIBUTION OF VELOCITY. The distribution of air velocities about the mouth of an exhaust outlet determines the effectiveness of the exhaust as a means of removing contaminants. In the hypothetical situation pictured in Figure 14 the area of the pipe opening is A and the velocity of the air at the opening, V. The total quantity of air passing into the pipe is $Q = AV$.

This same quantity of air is passing through any concentric spherical surface such as S at a distance x. Let its velocity be v. The area of this surface is $4\pi x^2 = 12.56x^2$. Again quantity equals area times velocity, so that

$$Q = 12.56x^2v$$

This suggests the theoretical relation between the velocity of air movement at any point, distant x from the exhaust opening when the air is being exhausted at the rate Q. We may take Q in cubic feet per minute, x in feet, and v in feet per minute.

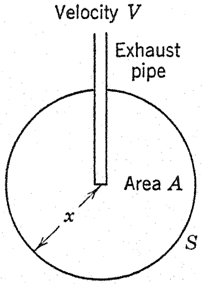
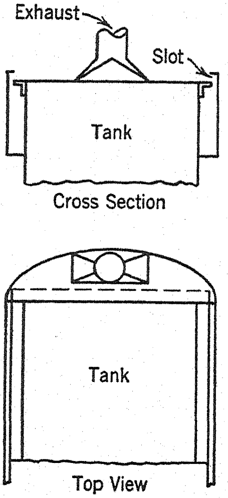


FIG. 14. Distribution of air velocities about an exhaust pipe.



Courtesy New York State Department of Labor

FIG. 15. Ventilation of an open tank by means of side slots.

In practice, the area of the duct itself, taken as small and omitted in the foregoing, modifies the results, and the expression,

$$Q = v(10x^2 + A)$$

has been found, experimentally, to hold. This defines the axial distribution of air velocities, in feet per minute, in front of the open end of an exhaust duct through which air is being withdrawn at a rate of Q cubic feet per minute, the area of the duct opening being A square feet.

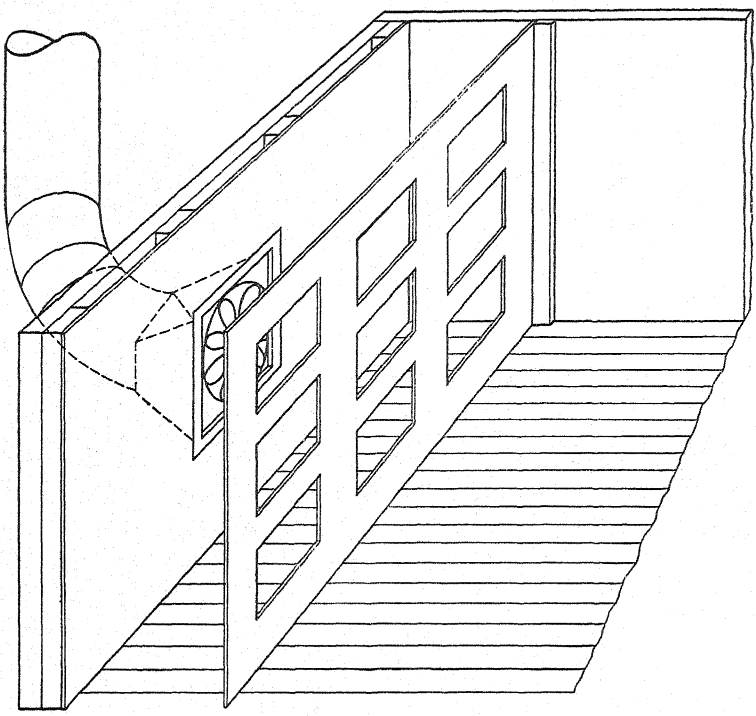
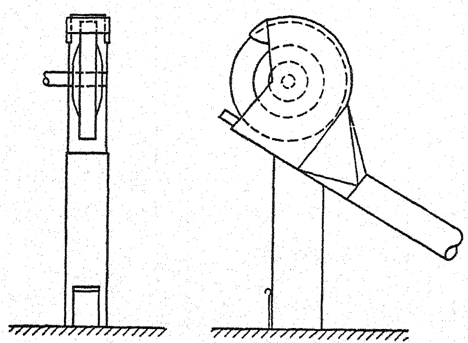


FIG. 16. Exhaust ventilation of a booth for spray painting of large objects.



Courtesy New York State Department of Labor

FIG. 17. Exhaust ventilation of a grinding wheel.

Exhaust ventilation may be successfully applied to open-surface tanks from which acid fumes or other objectionable vapors are given off. This is best done by an overhead hood, but, in situations where the space above must be kept clear for the operation, side-slot ventilation is feasible. This is illustrated in Figure 15.

The ventilation of small booths, capable of containing objects up to the size of an automobile truck, is accomplished by drawing air in through the open front end and distributing the flow transversely by means of suitable baffles. This is shown in Figure 16. Exhaust ventilation by more complete enclosure is illustrated in the grinding-wheel installation, Figure 17.

Exhaust ventilation may be quite successful in the removal of objectionable contaminants from the atmosphere of the workroom, but it also creates a problem of ultimate disposal. The treatment of the exhaust air with its contained impurities is dealt with in the discussion of atmospheric pollution in its more general aspects.

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CHAPTER 6

ILLUMINATING AND LIGHTING

Housing, taken in its broad general meaning, protection against the elements, introduces certain secondary problems in environmental control. One of these, as we have seen, is ventilation. Natural or daylight illumination likewise requires our consideration only as a result of housing or enclosure, whereas artificial lighting is more properly an independent protective adaptation against darkness. The lighting of dwellings, schools, offices, and workships has become recognized as an environmental factor in human welfare and efficiency, and its standardization and application comes within the scope of public health engineering.

Among the uses of lighting it is convenient to distinguish:

Street and highway lighting for safety.
Store and advertising lighting for display windows, counters and signs.
Lighting of homes, offices, and factories for vision and safety.

Our chief interest centers naturally in the last of these functions and thus in lighting as an adjunct to housing.

COMPARISON WITH VENTILATION

Like the air we breathe daylight comes to us naturally and freely. If mankind lived in the open and slept during the hours of darkness, there would be no lighting problem. In this and certain other aspects, lighting and ventilation have something in common, and both arts have progressed along somewhat similar lines. In each instance the initial problem has been the amelioration of a condition imposed by artificial housing, and in neither has progress been halted at the original objective.

In ventilation the simple purpose of supplying *fresh air* within the dwelling was first augmented by heating the air, and modern engineering has added all the other improvements included in air conditioning. Similarly, not only have the shortcomings of natural lighting been corrected, but present-day lighting makes possible

24-hour illumination of a constancy, reliability, and general availability impossible under natural conditions.

PUBLIC HEALTH ASPECTS

There are two distinct public health aspects of lighting. One deals with the relation of lighting to the hygiene of the eye, and with the correlated matter of effective output in shop or office; the other, with the germicidal and therapeutic properties of light, especially sunlight.

Light and Vision. Poor lighting produces ocular symptoms, rather obscurely described as eye strain and ocular fatigue. These effects may be regarded as rather minor in the list of human ills but they are far-reaching. Tests of factory output in a rather fine mechanical operation, inspection of small machine parts, have shown steadily increasing rates of performance with increasing illumination up to an intensity of at least twice that usually recommended for this type of work and four times the legally prescribed minimum.

In ventilation studies even less marked results than this would be held to represent a definite hygienic improvement. The cause and effect relationship, so clearly indicated in these and similar studies, may with equal propriety be held to prove that the greater intensity of illumination provides an environment better adapted to the physiological function of seeing and, thus, a more hygienic environment.

The actual results of such an unfavorable environmental factor as a polluted water supply are not confined to an increased death rate, but, in addition—and perhaps of even greater total significance—may encompass lost time, decreased output, and lowered physical well-being; in brief a loss in human capital. If this be a subject within the province of sanitary science it is equally within that province to study and to control those more obscure environmental factors, the effects of which are of similar nature and possibly may prove to be, when fully evaluated, of comparable magnitude.

Light and General Hygiene. The desirability of light, especially sunlight, in the home is so universally felt and conceded as to have become folklore, if not something even more deep-seated. Discovery of the relations between sunlight and rickets and, later, of the interrelations among ultraviolet light (solar or artificial), vitamin D and the calcium-phosphorous metabolism of the human body, provided a solid scientific basis for our inherited sun worship. There are various other *apparent* inverse relations between sunlight and diseases which, although suggestive, remain to be evaluated.

THE GERMICIDAL PROPERTY OF LIGHT. A long list of investigations, including the classic and pioneering work of the great bacteriologist, Robert Koch (1843–1910), had established the fact that light is germicidal, years before the discovery that the greater part of this property resides in the invisible ultraviolet rays. Recent interest in the powerful effects attributable to ultraviolet light have tended to obscure somewhat the fact, much more useful in our daily lives, that all light is germicidal. Koch's experiments were made by exposing bacterial cultures in glass, opaque to the ultraviolet. More recently it has been shown that the tuberculosis organism can be killed or inactivated even under colored glasses as is indicated in Table 18.*

TABLE 18

EFFECT OF LIGHT ON THE TUBERCULOSIS ORGANISM (WEINZIRL)

Glass	Time to Kill, Min
Colorless	5–10
Blue	10–20
Red	20–30
Green	45

A series of studies carried out in the author's laboratory at the College of Physicians and Surgeons of Columbia University, had for its object the evaluation of the lethal effects of daylight in simulated room environments. In all cases the bacteria, contained in glass-covered petri plates, were exposed to light which had passed through a normally clean windowpane. The light had, therefore, passed through two layers of glass.

A summary of a few of the results is given in Table 19. The *median survival time*, a convenient measure of the effectiveness of the light, is the time required for the inactivation or death of 50 per cent of the initial number of organisms.

In the series of experiments made with the alpha hemolytic streptococcus, sky conditions were recorded, and the intensity of the light was measured in foot-candles. Assuming the response to light of varying intensities to be linear, the data were reduced to the unit *median survival time per foot-candle of light*. A comparison of the quality of the light with its lethal effect indicated that, whereas

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* J. Weinzirl, *J. Infectious Diseases*, supplement 3, 128, 1907.

TABLE 19

Germicidal Properties of Light
(Buchbinder et al.)*

Organism	Median Survival Time† Daylight, Min	Dark, Hr
Alpha hemolytic streptococcus	44‡	26
Pneumococcus, types 1, 2, and 3	42	12
Beta hemolytic streptococcus		
Group *A*	252	65
Group *B*	66	132

* L. Buchbinder et al., *J. Bact.*, **42**, 353, 1941; **43**, 545, 1942.

† 50 per cent survival.

‡ Direct sunlight, through glass, 5 minutes.

an overcast sky gave more illumination within the room than did a clear blue sky, the effectiveness per foot-candle of the blue light was greatest, and decreased progressively through *few clouds, many clouds,* and *grey overcast* conditions.

The direct sunlight, although it could not be measured with so great accuracy on the foot-candle meter, yielded results per foot-candle of illumination that were inferior to those from the sky. It contains a large component of yellow, to which, incidentally, the foot-candle meter is especially sensitive. This lowers its average effectiveness when reduced to unit illumination. Its greater intensity, of course, makes it exceedingly powerful as a germicidal agent, as is indicated in the median survival time of 5 minutes, for the single species tested. There is reason to believe that the relative effectiveness between sky and direct sun, shown in this test would hold in general.

There is adequate justification, therefore, for the recommendation in *Housing for Health* which reads:

> Provision for admission of direct sunlight.
>
> No definite quantitative limits can be set but it is clearly desirable for all dwellings, and essential for those occupied by persons who are housebound, that direct sunlight should enter at some places and hours, especially in winter.

With this brief reference to the physiological benefits of sunlight, we shall devote the remainder of this chapter to its major topic, illumination and lighting as related to the hygiene of vision.

PHYSICAL PRINCIPLES

THE NATURE OF LIGHT

THE RADIATION SPECTRUM. Radiant energy is propagated through space in the absence of material substance. It may be pictured as traveling in waves of specific wave lengths which give to the various "kinds" of radiant energy their specific properties. The entire electromagnetic or radiation spectrum is probably continuous, and a large section of it is known to physicists, extending almost uninterruptedly from the *Roentgen* or *X rays* having wave lengths of the order of 1000 angstroms* to the *radio waves* ranging in length from centimeters to thousands of meters.

LIGHT. Light to the physicist is one small portion of this spectrum. To the physiologist it is identified merely by its relation to the sense of seeing. It comprises radiations within the comparatively narrow region of less than one octave between the approximate wave lengths 3950 angstroms and 7650 angstroms. A part of the so-called *ultraviolet light,* invisible to the normal eye, illuminates objects so that they can be seen by one whose crystalline lens has been removed by surgical operation for cataract. Thus, it is truly light illustrating the wholly arbitrary nature of our definition.

Not only does the band of wave lengths which constitute light excite vision, but also the stimulus of each separate wave length gives rise to a unique response, color sensation. The colors of the spectrum change, as do the wave lengths which cause them, by imperceptible degrees from deep violet to dark red. For purposes of approximate definition and orientation we may set down the wave lengths corresponding to certain *color areas* about as shown in Table 20.

TABLE 20

Color	Wave Length, A
Violet	4000
Blue	4500
Green	5000
Yellow	6000
Red	7000

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* The angstrom unit, A = 10^{-10} meter. Other units frequently employed are the millimicron, $m\mu = 10A = 10^{-9}$ meter, and, for the longer waves, the millimeter and the meter.

These are monochromatic colors associated with wave lengths. When various colors are superimposed the eye synthesizes a new color impression. Thus there is a green corresponding to a single wave length, but the eye also "sees" a green when yellow and blue are superimposed upon the retina. The trained eye of the artist can analyze such a compound sensation into its components.

PHYSICAL MEASUREMENT

It will serve to illustrate and emphasize the peculiar nature of light as a physiological response if we digress briefly and consider the nature of measurements in general.

UNITS OF MEASUREMENT. The metric unit of length, the meter, is strictly defined as the distance between two marks on a certain bar of platinum alloy preserved at Paris. Copies, in other places, serve as units only because they duplicate the primary standard within the limits of error that represent the most accurate comparison possible at the present time.

The same is true of the standard kilogram, which is singularly defined as the weight of one certain piece of metal. Each of these standards is a specified sample of the property to be measured, a sample of length or a sample of mass. Measurement consists in applying the sample to the quantity to be measured, and reporting the result as a ratio.

The basic unit of time is also a certain sample, the length of time required for the earth to complete a daily rotation about its axis.

Most other physical units, velocity, acceleration, force, energy, and the like, are merely combinations of the three basic units of length, mass, and time. Radiant energy is measurable in energy units, ergs, or in equivalent heat units. The Weather Bureau reports the rate of input of solar energy at the earth's surface at a given time and place in *calories per second per square centimeter*. Light too, as a form of energy, can be measured in thermal or work units. In fact the total solar energy previously referred to includes the energy of the light received from the sun.

For vision, however, a new characteristic of light, its power to stimulate vision, is involved. It depends on the quality (wave length) as well as on the quantity of energy. The eye sees only a certain portion of the radiation spectrum and sees some portions—for example, yellow—more strongly, per unit of energy, than others—red or blue. At each end the visible spectrum fades gradually into invisibility. Thus, if it were attempted to measure illumination in terms of energy, the measurement would involve a summation of the energy content of each individual wave length times a specific physiological factor, the radiant luminous efficiency of that wave length, to convert energy into *seeing*.

LIGHT UNITS

For these reasons a set of light units is employed in the study of illumination which is largely independent of the formal units of physics. These light units are based on *visual* comparisons of any given illumination or system of lighting with certain standards of the same sort.

THE LUMEN. The unit of light flux is the lumen. It is essentially a rate, measuring the flow of light, just as the watt measures the flow of electric energy. The consumer pays for a lumen-hour on his electric bills. Because seeing is an instantaneous act, it is convenient to regard the lumen as a quantity of light, leading to a given state of illumination, rather than a rate of flow.

Notwithstanding the absence of fixed relationship between radiant energy and luminous intensity, a converse relation can be formulated. Watts, in general, are not translatable into lumens, but lumens do represent watts. Within the visual range of radiation, and with such mixtures of wave lengths as are given off by the sun or by artificial sources employed in lighting, one lumen of light represents very nearly 0.0015 watt of energy. One watt of this luminous energy therefore amounts to about 667 (1/0.0015) lumens.

If we take the luminous output of a 100-watt Mazda C lamp at 13 lumens per watt of applied electric energy, it requires about 51 watts to produce 667 lumens, the luminous energy equivalent to one watt. Such a lamp, therefore, has an over-all radiant luminous efficiency of about 2 per cent. This seemingly imperfect and inefficient result represents, in fact, a great advance in lighting science as indicated in Table 21. Progress appears to be continuous in the direction of greater luminous output per unit of applied energy.

CANDLE POWER. The lumen is the basis of rating lighting fixtures —*luminaires*—and of measuring light flux. Its definition, however, depends on a more fundamental and much older unit, the *candle*

TABLE 21

LUMINOUS EFFICIENCY OF VARIOUS LIGHT SOURCES

Source	Lumens per Watt
Open-flame gas burner	0.22
Petroleum lamp	0.26
Carbon-filament lamp	2.6
Tungsten-filament lamp	8.0
Mazda C lamp	12.0–16.0
Fluorescent lamp	30–60
Open-arc lamps for street lighting	
Carbon	11.8
Magnetite	21.6
White flame	29.0
Yellow flame	34.0

power. Originally, the candle power was a measure of the luminous output of a candle. Even today, the so-called standard sperm candle is employed as a standard in the measurement of light. In various countries, other sources are used, generally a lamp of specified construction and dimensions burning a specified substance, often a pure chemical such as pentane or amyl acetate, at a standard rate of combustion. These various sources have been compared and standardized by international agreement in terms of the *International candle*.

The candle power of a light source measures the intensity of the light in one direction. The total flux from a source may be distributed fairly uniformly about the surrounding sphere, or it may be concentrated, by reflectors and lenses, into a narrow beam. The total output, in lumens, remains essentially constant, being reduced somewhat by reflection; but, in the direction of the beam, the candle power is intensified. Thus lumens measure total emission, and candle power is directional and represents concentration or intensity of emission within a given solid angle or cone.

The mean spherical candle power is the mean intensity along every radius of the surrounding sphere. Summation of the intensity about the sphere is readily made by suitable optical arrangements. Obviously this value is related to lumens, a relation to be developed presently.

THE FOOT-CANDLE. The effect of luminous emission of given intensity is to produce a proportionate illumination. It is illumination, not candle power or lumens, by which we see. The unit of illumination, or of luminous flux, per unit of illuminated surface, is *the foot-candle*. As the name suggests, it is *the illumination produced on a surface which is one foot distant from a source of one candle power and normal to its rays.*

The *lumen* may now be defined as *the radiant flux that will produce an illumination of one foot-candle over an area of one square foot.* With this definition, the relation between mean spherical candle power and lumens may be derived. Given a sphere of one foot radius, its surface area is 4π, or 12.56 square feet. Place at the center of this sphere a light source of 12.56 lumens uniformly distributed. By definition, the surface will be illuminated at one foot-candle. But a source which illuminates a surface one foot distant at one foot-candle is, by definition, one candle power. Hence one mean spherical candle power is equivalent to 12.56 lumens.

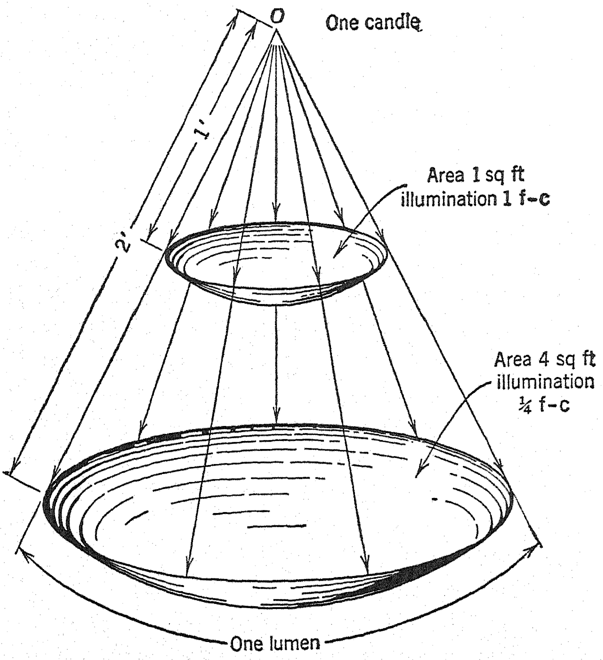

FIG. 18. The inverse-square law and the relations among the units of light intensity, luminous flux, and illumination.

GEOMETRIC REPRESENTATION. The mutual relationships between lumens, candle power, and foot-candles can best be shown in geometric form. In Figure 18, a point source of light at *O* has a uniformly distributed intensity of one candle power. At a distance of one foot is a spherical zone having a surface area of one square foot.

The illumination of this surface is one foot-candle, and the quantity of luminous flux contained within the solid angle of the cone is one lumen. The complete spherical surface has an area of 12.56 square feet, and the total emission is 12.56 lumens.

Brightness. Brightness is the total intensity of a luminous source, viewed from a given direction, divided by its area normal to that direction. The unit of brightness is the *candle per square inch*. Since both the intensity and apparent size vary inversely with the square of the distance (see p. 126), brightness is independent of the distance from which the light source is viewed. It is, therefore, commonly called *intrinsic brightness*. Brightness and illumination are of the same nature but are expressed in different units. A plain surface, *diffusing* 452 foot candles *of illumination* would have a brightness as viewed at right angles to the surface, of one candle per square inch. Brightness remains the same when viewed from any angle if it be referred to an *apparent* square inch or a square inch perpendicular to the line of vision. Regarded as a source of light, however, the mean spherical candle power of this surface would be only one-fourth candle per square inch as a result of the operation of Lambert's law (p. 128).

Illuminating engineers now generally prefer a less ambiguous unit of brightness, *lumens per square foot*. This is the illumination in foot candles *times the reflection factor* and is called the foot-lambert in reference to the metric units *lambert* and *millilambert* (see infra).

Summary of Units. The various units employed in illuminating engineering and their interrelationships are summarized in Table 22.

Metric System Units. In the metric system the units of directional intensity and of quantity of light, the candle and the lumen, respectively, are the same as the English units. The unit of illumination is the *lux*. This is the meter-candle, corresponding to the foot-candle, that is, the illumination on a surface at a distance of one meter—3.281 feet—from a source of one candle. By the inverse square rule (p. 126), one foot-candle is 3.281^2, or 10.765 lux, and one lux is 1/10.765, or 0.0929 foot-candle. One lux of illumination is produced by the incidence of one lumen of light upon a surface area of one square meter.

The small value of the lux makes it convenient to employ a secondary unit, the *phot*. This is the illumination of a surface at one centimeter from a source of one candle, or the illumination of one square centimeter by one lumen. Numerically, therefore, one phot is equivalent to 10,000 lux and to 929 foot-candles.

The metric unit of brightness is the *lambert,* which is the brightness of a surface emitting one lumen per square centimeter in a direction normal to the surface (normal brightness). The *foot-lambert* described earlier is numerically equivalent to 1.076 *millilambert.*

TABLE 22

SUMMARY OF UNITS

Unit of	Name	Symbol	Derivation
Intensity	International candle	I	Fundamental
Illumination	Foot-candle	E	$E = I/R^2$
Luminous flux	Lumen	F	$F = 12.56I$
Brightness	Candles per square inch or	b_o	$b_o = E/452$
	lumens per square foot	b_o	$b_o = E$

The brightness defined by b_o is "normal brightness," that is, the brightness viewed from a direction normal to the surface. From other directions differing from the normal by x, the brightness is given approximately by Lambert's law, $b = b_o \cos x$.

SOME USEFUL LAWS

THE LAW OF INVERSE SQUARE DISTANCES. The law of inverse square distances is of maximum usefulness in the study of the distribution of light. It may readily be derived from geometric considerations. With reference again to Figure 18, light emitted from the point source O of one candle power uniformly illuminates the spherical zone at one foot distance at an intensity of one foot-candle. Now the spherical zone at 2-foot radius has a surface area of 4 square feet and receives the same quantity of light, namely, the one lumen within the cone. Hence, the intensity of illumination on the zone at 2 feet is one-fourth that on the zone at one foot. In general, *the intensity of illumination from a fixed source of radially distributed light varies inversely as the square of the distance from the source.* The rule would not apply, of course, to parallel beams emanating from a parabolic reflector such as is employed in a searchlight.

THE COSINE LAW. The angle of incidence of light on an illuminated surface is the angle made by the rays with a line perpendicular to the surface. Illumination is maximum when the rays strike perpendicularly and falls off as the angle of incidence increases. In Figure 19 let the lines *a* and *b* represent the intercepts of two planes perpendicular to the plane of the paper. The areas of the two planes are then as *a* to *b*. Let the angle between the planes be α; this is seen, by the geometric relation, to be equal to the angle of incidence *i*. The same total *quantity* of light is incident on plane *a*, at angle *i*, or, alternatively, on plane *b* at normal incidence. But the illumination on *a* is less than on *b* in inverse relation to their respective areas, or b/a, which is the cosine of *i*. Hence:

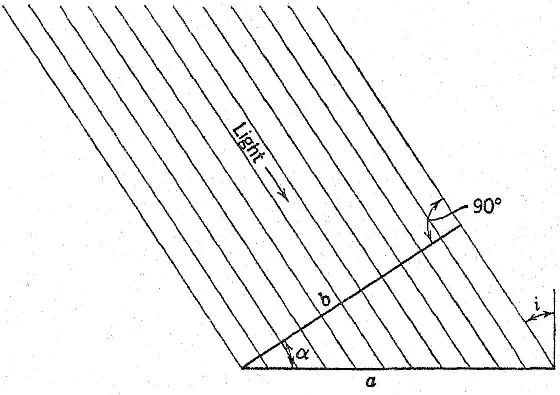

FIG. 19. The cosine law.

The intensity of illumination from a given source upon a plane varies as the cosine of the angle of incidence.

REFLECTION. Reflection of light plays an important role in illumination. Its influence can be imagined if one thinks of a room with black walls, floor, ceiling, and furnishings. Ordinarily, much of the total illumination in a room comes by way of reflection from objects in the room, particularly from light-colored walls and ceiling.

Reflection may be specular, as from a mirror; diffusive, as from a dull surface; or a mixture of the two. Practically all reflections are of the mixed type. In specular reflection the incident ray rebounds from the surface after the manner of a tennis ball. The angle of reflection is equal to the angle of incidence. There is, however, some scattering (diffusion) from a mirror surface.

Purely diffusive reflection is even less common. It would yield a distribution similar to that shown for Lambert's law. Regardless of the angle of incidence of a ray, it would be reflected in all directions from the surface at an intensity proportional to the cosine of the angle of reflection. The two limiting ideal cases and an intermediate case of mixed type are shown in Figure 20.

The *proportion* of the incident light which is reflected is also an important characteristic of a reflecting surface. It is related to the color, texture, and "whiteness" or "blackness" of the surface. A good grade of white bond paper has a *reflection* factor approximating 80 per cent; a dingy wallpaper may reflect only 5 or 10 per cent of the incident light.

LAMBERT'S LAW. The brightness of any surface observed or measured in a direction making any angle with the normal decreases as the angle increases. A perfectly diffusing surface, one in which there is no direct reflection of incident light, emits diffused light according to Lambert's law, which states that the intensity of emitted light, in any direction, making a given angle with the normal, is proportional to the cosine of that angle, or

$$b = b_o \cos \alpha$$

b being the brightness in the direction α from the normal and, b_o being the normal brightness.

THE DISTRIBUTION DIAGRAM. Lambert's law provides a favorable illustration of a graphic method, frequently employed in recording the distribution of light from any source. In Figure 20*B*, *O* is a point on a bright diffusing surface; the surface of a frosted globe illuminated from within or a nonglossy reflecting surface.

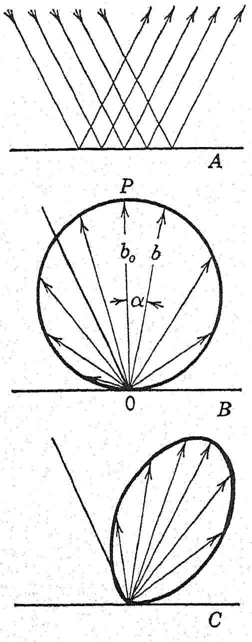

FIG. 20. Types of reflection.

A Specular;
B Purely diffusive;
C Mixed.

Construct a circle tangent to this surface at *O*, and erect the perpendicular diameter *OP* of length b_o. Let the line b making angle α with *OP* represent any other direction from *O*. Then Lambert's law states that the intensity of light flux along b is to that along *OP*, as the cosine of angle α, or as b/b_o. Hence, lines drawn in any direction from *O* to the circumference of the circle represent by their lengths the relative intensity of light in that direction.

This illustration represents a theoretically perfect diffusion. The distribution diagram, however, may be employed to represent any other condition of distribution as is illustrated in Figure 20*C*.

PHOTOMETRY

Photometry, or the measurement of light, is necessarily a visual process, because seeing is the ultimate basis of comparison. All photometry goes back ultimately to the inverse-square law. If two light sources, one a standard source and the other a source the intensity of which is being measured, can be made to illuminate a surface equally by locating the more intense source at the greater distance, then the two intensities are inversely as the squares of the respective distances.

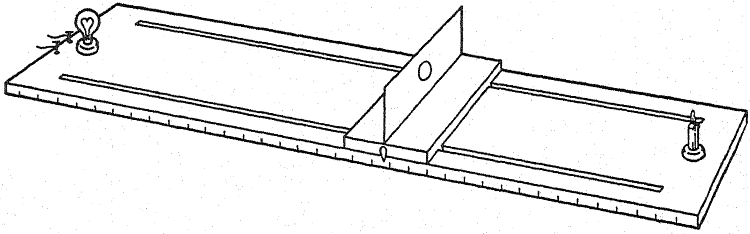

Fig. 21. A simple Bunsen photometer.

The Bunsen Photometer. A very simple device, which can be used to make this comparison, is a piece of thin paper on which a drop of oil has been placed and allowed to soak through. If the paper is held up to the window, the oil spot appears lighter than the paper; if the paper is held in the opposite direction, the spot appears darker. This difference is due to the unequal illumination on the two sides and to the fact that the light is transmitted more readily through the spot than through the paper itself.

By placing such a prepared paper between two sources of light, its position can be adjusted so that the oil spot becomes almost invisible. The two sides are now illuminated equally, and the relative intensities of the two sources are readily determined, Figure 21. Photometers employing this basic principle are made with greatly improved mechanical and optical arrangements of various kinds.

Photovoltaic Measurement. When light falls on certain metal surfaces, suitably connected in an electric circuit, with or without an applied voltage, electrons are released in numbers proportional to the radiation intensity within certain wave length ranges, according to the metal employed. This is the photoelectric cell, or, in instruments in which the voltage is developed wholly within the instrument, the photovoltaic cell. The light meters commonly used by photographers are of the latter type, as are the foot-candle meters now commonly employed in measuring illumination.

Light meters are secondary standards of comparison. They measure energy, not *seeing,* but, by use of appropriate metals, they can be made to approximate the visual response. They are calibrated against a standard light source to read directly in foot-candles of illumination and are now quite indispensable in making illumination surveys of a factory or office.

The Globe Photometer. It has been noted that the luminous output of a light source, such as an electric lamp, can be measured in candles in any one direction; that the candle power thus measured will vary greatly in the various directions; and that the output, measured in total lumens, is proportional to the mean spherical candle power.

The mean spherical candle power is measured in a device known as the *globe photometer.* This is a hollow globe, several feet in diameter. Its inner surface is coated with a substance of highly reflective and dispersive properties, such as magnesia. The lamp is placed in the center of this globe and its light is reflected and dispersed in all directions at each contact with the wall. Eventually, the illumination in any direction is exactly that in any other, and represents the mean spherical candle power of the lamp modified by the many reflections. This modifying factor for the instrument is determined by inserting a standard lamp and viewing the interior through any type of photometer. The comparison lamp is then inserted and similarly measured, and its total luminous output is thus determined.

PHYSIOLOGICAL ASPECTS OF VISION

Any comprehensive review of the current, and often conflicting, theories of human vision would go far beyond the requirements of our present interests. There are, however, certain facts concerning the eye functions which will be of assistance in drawing specifications for satisfactory lighting.

SEEING

The eye *sees* objects and outlines only by contrast. Binocular vision, the focusing of the lens and perspective enable it to *perceive* the depth of three-dimensional views; but, before this is possible, portions of the field must be distinguished from adjacent portions. If these areas possess no distinguishing contrast they appear as one. Contrast is of several sorts.

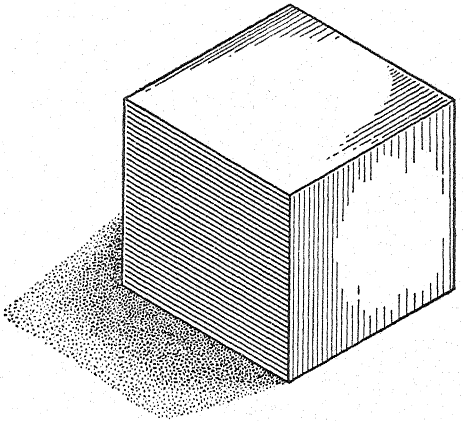

FIG. 22. Perception of three dimensions by brightness contrast.

BRIGHTNESS CONTRAST. A disk of white paper, laid on a sheet of the same paper, may be seen in outline by a slight shadow around the circumference. Shade and shadow are of great aid in distinguishing form and depth. A cube, of uniform color, viewed centrally above one corner, with one eye, is merely a regular hexagon in outline and would be so seen if uniformly illuminated. The inevitable unevenness of lighting, however, brings out three rhombs of different brightness, and the eye perceives a three-dimensioned cube as the most logical interpretation of the two-dimensioned retinal image. This is *perception* as distinguished from *seeing* (Figure 22).

The effectiveness of brightness contrast is quantitative, not relative

A slightly gray disk on a white ground may be seen in good illumination with a difference in reflecting power of, let us say, 2 per cent. This is the relative apparent brightness of the two areas; it will be maintained at any intensity of illumination. If now the illumination be reduced to a very low value, it may require a difference of 10 per cent in reflecting power to make the disk visible. The principle is obvious if we consider the limit of no illumination. Then even black on white becomes invisible.

Whereas some degree of brightness contrast is helpful in seeing, too great contrast renders seeing more difficult and less efficient. This point is discussed more fully under glare and shadows (p. 143).

Color Contrast. An oil painting is seen almost wholly by color contrast. We see many objects because they differ in color from adjacent areas of the visual field.

Objectively, color is wave length, or, in nature, a mixture of wave lengths, *reflected* by the object. *White light* cannot be defined except as that mixture of wave lengths which comes from the sun and sky as reflected and modified by the surroundings.

A white paper, on the other hand, is one which has no selective absorption. It reflects all colors equally and, by a certain percentage, its reflection coefficient. High reflection coefficients yield a white; lesser coefficients, neutral grays; and a theoretical zero coefficient, an ideal black. A very white paper may reflect 80 per cent of the incident light. It is not, therefore, a perfect white. A perfect black is equally difficult to imagine.

A white or neutral gray paper, reflecting all wave lengths, appears red in red light and green in green light. A red paper, on the other hand, reflects only red rays and thus appears red in white light and nearly the same in red light.

Subjectively, color is discrimination of wave length by the retina. For the normal human eye, radiation has a maximum visibility per energy content, in the region of the yellow-green, or about 5550 angstroms. It falls off in each direction to about 3900 angstroms in the violet, and to about 7700 angstroms in the red. The great variety of colors that may be differentiated result from the ability of the eye to blend superimposed color and to synthesize.

Reflection. Under equal illuminations two surfaces may appear in contrast by reason of dissimilar reflection characteristics. Thus, the specular reflection from the *cut* behind a lathe tool makes the surface stand out in contrast to other areas of the same color and illumination. A *gloss* as against a *matte* surface will differentiate two pieces of paper of the same color and brightness.

It has perhaps already been noted that the color of an object is, in reality, the expression of its characteristic properties with regard to the absorption or reflection of light of various wave lengths; and that brightness, under a given illumination, is merely a measure of reflection.

Texture. That quality which is best described as texture is generally associated with the feel of an object. However, wood and stone, cotton and silk, black felt and black fur are generally distinguishable by sight. An artist can depict satin robes, glass dishes and the human skin with fidelity. This quality of texture is probably compounded of color and reflection, but these are so intricately blended as to require the touch of the artist to analyze and reproduce them. In everyday life we see and discern much by texture contrast.

QUANTITATIVE MEASURES OF SEEING

Subjective tests of the efficacy of a given illumination or of the relative advantages of illuminations of different intensities or quality are not readily devised or applied. Two such tests will be referred to.

Acuity of Vision. If a set of closely spaced black lines on a white ground are kept in view as they are gradually moved away from the subject, a point is reached at which they will have merged into a general gray field. The ability of the eye, as of a microscope lens, to separate closely spaced objects is known as its *resolving power*. It is largely a matter of subtended angle. If the scale of the object, both width of lines and spaces, be doubled, the lines may be resolved at twice the distance. Any newspaper reproduction of a photograph serves as a good illustration of resolving power. Closely inspected, it is seen to be made up of fine lines and dots. At a slight distance, these merge into smooth areas of lighter and darker shade, according to their width and spacing.

Resolving power, alone, is the older and better-established definition of *visual acuity*. For the purpose of standard comparisons, normal acuity is placed at the ability to resolve lines and spaces which subtend an angle of one minute at the eye. The standard Snellen chart consists of black letters such as **E**, which are normally identified at such a distance that the entire letter subtends an angle of 5 minutes, and each stroke or space, an angle of 1 minute. The letter shown here, for example, subtends these angles at 8.0 feet and would normally be identified at that distance.

Recent writers have somewhat broadened the concept of acuity and have analyzed it into

(*a*) Ability to see a small object—or a dot.
(*b*) Ability to separate lines.
(*c*) Ability to read (identify a letter).

The last of these includes psychological factors. At the limit of acuity, an English letter might be readily interpreted, whereas a Chinese character would not register.

The optometrist employs the test of acuity, under adequate illumination, as a measure of the quality of vision and to guide him in the correction of errors of refraction and accommodation in the eye. With normal eyes and a varying illumination, the same test can be employed to measure adequacy of illumination.

Employed in this manner the test shows that, on a good diffusing white background, the visual acuity increases progressively with increasing illumination, at first rapidly and then more slowly, up to about 10 foot-candles. Above this intensity of illumination the increase in acuity is slight, but still measurable.

With a background having a lower reflection factor, the intensity of illumination required for a given degree of resolution increases proportionately. Thus, with a paper having a reflection factor of only 40 per cent, the illumination required for the same visual acuity is twice that required with one of 80 per cent reflection factor.

SPEED OF VISION. In many occupations, such as that of postal clerks engaged in sorting mail, the time required to see and interpret the object mentally is of importance. This time is also inversely associated with accuracy. Working tests of speed are based on a criterion of rate of sorting, keeping within a specified limit of percentage accuracy. Laboratory tests are made by suddenly illuminating the object for a limited short time. At the lower limit of visual acuity an object may be resolved and discriminated only after a certain period of fixed observation or staring. At closer range or in better light, it might be discerned more quickly. Speed of vision enters prominently into the very practical but complex matter, speed of reading.

proximately parallel with acuity, the time required to see and perceive decreasing rapidly with increasing illumination up to about 10 or 12 foot-candles, then more slowly but continuously.

THE PRACTICAL BASIS OF LIGHTING

QUANTITY OF LIGHT

The ill effects of continuous use of the eyes in close work and under insufficient illumination are generally known or appreciated subjectively. Eye strain, eye fatigue, and headache are the more commonly reported symptoms. Objective tests are all but lacking, and there appear to be but few, if any, reliable physiological data on which to base criteria of satisfactory illumination. The tendency in the past has been toward economy, and the early codes, fixing minimum permissible illumination intensities, were rather closely adhered to, as representing optimum values.

At present the tendency is in the opposite direction. The increasing use of electricity in the home and in industry, together with improvement in generating machinery, has resulted in a marked and apparently continuing decrease in the cost of electric energy. Research has also improved the efficiency of the lamp itself, measured in lumens per watt (see p. 123). The result has been a continuous decrease in the cost of lighting. This basic fact, in conjunction with a rather active and appealing sales campaign on the part of the commercial interests involved, has tended to take the issue out of the realm of scientific standardization into one of aesthetics, modernization, and changing style.

It is often presumed that the ability to perform a given task comfortably, speedily, and accurately provides a satisfactory measure of an environmental condition. It is always possible, however, that increased output may be accomplished at the expense of the machine; that, in the long run, conservation of the bodily function represents the greater good. Let us then approach the question of optimum seeing conditions from each of these points of view.

Conservation of Vision. Throughout the various discussions of lighting, and especially of the optimum intensity of illumination, the opinions and the research of the ophthalmologist have been noticeably lacking. A recent communication addressed to the members of this profession by two of their associates* indicates that this situation is due, not so much to lack of scientific interest as to the fact that no critical problem is at issue. More stress is laid by these authors on the quality and the proper distribution of the light than on its actual intensity.

They note that in 1896 Katz found the best average illumination, when speed of reading was involved, to be 0.4 foot-candle; that most authors up to 1912 recommended 2 to 4 foot-candles as optimum; and that Trolland in 1931 "after the most extensive review of the literature on this subject ever undertaken," concluded that the majority of industrial operations can be carried out at maximum efficiency at illumination intensities of about 10 foot-candles. On the other hand, Luckiesh of the General Electric Company favors "levels 50 to 100 times as high as those formerly considered optimum."

Hardy and Rand conclude that the explanation for these diverse findings lies in the adaptability of the human eye which can probably function efficiently over a range of illumination intensities of 10,000 to 1. They do not venture, therefore, to define an optimum within closer limits than to state that the effect on ocular fatigue of changes within the range 10 to 30 foot-candles is relatively unimportant; that continued use of the eyes, especially for fine work, under intensities of the order of one per cent of these values will result in eye strain and functional inefficiency with possible organic damage; and that intensities of artificial illumination of 100 times these values may also result in eye strain and ocular fatigue unless adjustment is made in the quality and distribution of the light.

The argument for high levels of intensity is frankly based on the proposition that the human eye is well adapted to daylight illumination of the order of hundreds of foot-candles, and that artificial illumination should approach these values for maximum benefits. Even if such a program is conducive to some extravagance in lighting costs, it has done a great deal of good in the improvement of lighting conditions in the home, school, and office, and is still far below the upper limit set by Hardy and Rand as possibly requiring some further adjustments in quality and distribution.

Productive Output. From the point of view of output, as distinguished from the conservation of vision, the best information available for the determination of optimum light intensities is that derived from practical tests of industrial operations. Here the results are in good agreement and indicate in general that more and better work is done with improved lighting. The gain is usually greatest in the lower ranges of increasing illumination, over the pre-existing conditions, and falls off in the higher ranges, as would be expected. However, it is seldom observed that the optimum intensity has been reached. The problem then resolves itself into an economic balance between the diminishing gain in productive output and the cost of additional lighting.

An example of this type of study is one made by the U. S. Public Health Service of the efficiency of postal clerks in sorting mail, a task representing a considerable part of the total man-hours of the postal service.* Some of the conclusions were:

> A relation has been shown between changes in illumination, and the amount of first-class mail sorted by the night clerks in the routine course of post-office work. No clearly marked relation was found to hold for the day clerks, nor for other classes of mail. The increase for the night clerks in sorting first-class mail, in going from an illumination of 2.7 to 10.7 foot-candles, appears to be about 8 per cent . . .
>
> In sorting of test cards, it was found that there was a relation between the time of sorting and the degree of illumination under which the tests were made, the looking time, or the time taken in looking at the addresses, decreasing about 8 per cent in going from 2.5 to 10 foot-candles. There was no relation between the illumination and the time taken in mechanical distribution. After eight or nine foot-candles were reached, there was no marked effect upon the sorting time. Errors diminished as the tests progressed, but no relation was found between the degree of illumination and the number of errors.
>
> There was a definite improvement in visual acuity after the subjects had worked under high illumination for a sufficient length of time and a corresponding decrease after working under low illumination.

STANDARDS AND CODES. The American Standards Association has established a scale of recommended light intensities applicable in the main to industrial conditions. Following is a summary of the recommendations, according to the type of activity or use.

American Standards Association Code (1932)

Foot-Candles Recommended

1. Aisles, stairways	2–3	6. Office—general, school	8–10
2. Washrooms	3–5	close work	10–15
3. Carpentry—benchwork	5–8	typing	12–20
4. Laundry, bakery	8–12	7. Glass cutting	15–50
5. Weaving light goods	8–12	8. Fine machine work, inspection	25–100
dark goods	12–20		
		9. Jewelry working, drafting	25–100

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* L. R. White et al., *U. S. Pub. Health Service, Pub. Health Bull.*, 181, 1929.

As illustration of the changes that have occurred in this field (and of the workings of the *rule of expediency,* p. 278), the minimum legal requirements and the *desirable* values for some of the same classifications, in 1924, were as follows:

Class	Minimum	Desirable
1	0.25	0.5–1.0
2–3	0.5	1.0–2.0
4	1.0	2.0–4.0
5	2.0	4.0–6.0
6	3.0	6.0–8.0
8–9	5.0	8.0–15.0

The American Standards Association code was established after careful consideration of all aspects of the particular matter by large committees of representative experts; it may safely be taken as a reasonable and well-considered set of illumination standards which will doubtless form the basis of the codes of the various state bodies, generally the labor departments. Boards of Education and school architects are in general agreement on the item of 10 foot-candles at the darkest corner of the classroom, to be provided, as far as possible, by daylight illumination, but with artificial illumination of the same value available.

QUALITY OF LIGHT

Light Sources. Daylight, to which the human eye is normally adapted, consists of a continuous band of wave lengths extending from the short-wave violet to the long-wave red. This light blends into the so-called *white*. The actual spectral composition of daylight varies from hour to hour and is modified by reflection from such colored objects as trees and buildings. It is basically a function of the temperature of the sun's surface, about 6000 degrees Kelvin, and has an energy peak in the yellow–green. Incandescent bodies at lower temperatures have spectra with energy peaks shifted toward the red. For this reason artificial lighting, even from the Mazda filament, appears yellow in daylight.

A much greater departure from the spectrum of sunlight is found in the light from the so-called *gas lamps* of the neon type. These lights are composed of only a few bright lines of the spectrum which blend into the characteristic colors of the lamps: orange, blue, green, and so on. The Cooper–Hewitt, or mercury-vapor lamp, frequently seen in photographer's windows, post offices, and factories, is of this type. It is an economical light, but almost monochromatic.

Spectral Quality and Vision. Good microscope and camera lenses are *achromatic;* that is, they bring light from all parts of the spectrum to about the same focus. The eye is not thus equipped, and, in dealing with a wide spectral band, it focuses on the more intense color, with a resultant color blurring of the image, which tends to limit acuity or resolving power. In a monochromatic light, visual acuity is greatly improved, as can readily be demonstrated by examining some such object as a postage stamp under this light. Despite the gross distortion of color values, better discrimination of detail is noted.

The question of the effect on the eye of working in a light in which the intensity is concentrated in a few lines of the spectrum does not seem to have been investigated. Personal questioning of men working all day in a drafting room under these lamps failed to elicit any complaints.

Color. Incandescent bodies, such as the heated filaments of electric lamps emit light in a continuous spectrum similar to that of the sun except for its distribution of energy. The energy peak and the form of the energy distribution is a function of the temperature of the filament. The hotter filaments produce the *bluer* light.

There are certain situations in which a natural daylight effect is desirable. In dry-goods stores, where color matching is important, the so-called *daylight fixtures,* provided with blue glass to filter out the excess orange, provide a very good imitation of the color of natural daylight. A still bluer light is preferred by the microscopist for better seeing. The shorter wave lengths themselves improve acuity, in addition to their more nearly monochromatic character.

Hardy and Rand find that certain individuals are able to work longer and with less fatigue under artificial daylight units than under the Mazda lamp. They do not admit to this category however the *blue-glass* bulbs sometimes called daylight bulbs which represent about a 15 per cent approach from the Mazda lamp to the light from a north sky.

The newer *fluorescent lamps* have color characteristics which are very largely under control by the manufacturer. Their primary output is invisible ultraviolet light. This acts upon a coating on the inner surface of the tube to yield a secondary light by fluorescence. A great variety of substances fluoresce under the influence of ultraviolet light and yield secondary light in a wide range of colors. By suitably blending certain of these *phosphors* a resultant light may be obtained which simulates natural daylight. For decorative and advertising purposes a wide range of colors is also available.

These lamps or tubes have a high yield of useful light per watt and are therefore economical. A high luminous efficiency means a low heat production; the tubes are relatively cool. This is an advantage in warm weather and in air-cooled homes.

Hardy and Rand point out that, despite the *simulation* of daylight, the spectral curve of the "daylight" tubes is not that of daylight and that many persons experience discomfort and unpleasantness while working under this light. Common complaints are ocular fatigue, burning of the eyes, tearing, and headache. This may be attributed in part to spectral quality but flicker, high intrinsic brightness, slight emission of ultraviolet light, time lag in the emission of the respective component colors, and the stroboscopic effect are all possibilities that are still under investigation.* Some of these characteristics of lighting systems are discussed more fully in later sections.

DISTRIBUTION OF LIGHT

An average illumination of 10 foot-candles, at workbench level, could be had from a single luminaire at the center of the room. The intensity, however, would vary from a maximum directly under the fixture to a minimum in the far corners. Both the inverse-square law and the cosine law work against the corner position, a greater distance and a poorer angle.

If the fixture were placed higher, the distribution would be better on both counts, but the total illumination would be less. Four fixtures evenly spaced about the room would improve distribution and, by producing four shadows instead of one, tend to reduce the disadvantage of sharp shadows. These considerations illustrate the problem of distribution as distinct from that of total illumination over an area.

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* These studies are being made at the Knapp Memorial Laboratories, Institute of Ophthalmology, Columbia University, Presbyterian Hospital, New York.

Reflection. If we recall the principle of the globe photometer (p. 130), it is obvious that much of the light that reaches the desk is reflected light. A glance about the room will indicate that all illuminated surfaces become light sources and that some are much brighter than others. This property is described as the *reflection factor*. If the light entering an enclosed space were totally reflected, one complete reflection of the initial ray would double the illumination of the space, and repeated reflections would cause it to approach infinite brightness. If one half of the light incident on the surface were reflected, successive reflections would increase the illumination due to an initial ray to

$$1 + \tfrac{1}{2} + \tfrac{1}{4} + \cdots$$

the sum of which series is two. In general, if the fraction F be reflected, the total illumination becomes $1/(1 - F)$.

The reflection factor of the walls and ceiling thus has considerable influence on the total quantity as well as on the distribution of the light in a room. A good clean white paint may reflect as much as 80 per cent of the incident light; a light tinted paint, 70 per cent; and dark wallpapers, as little as 10 per cent. Paint manufacturers are giving attention to this characteristic, and there have been important developments in the production of paints of high reflection factor.

Reflectors and Diffusing Globes. Important use is made of reflectors, as a part of the luminaire, to distribute the total lumens from the light source in the direction in which they may best be utilized. This is especially valuable in such places as shops with high ceilings or with many obstructing shafts and pipes, where good ceiling reflection can not be had. Instead of permitting half the illumination to escape into this nonreflecting area, a good reflector will send most of it into the lower hemisphere. Moreover, the shape of the reflector will determine the subsequent distribution. Street lights are usually provided with flat reflectors. These give a wide lateral distribution of the light which would otherwise illuminate the sky. In the shop, at the other extreme, a reflector of semi-egg-shape section will concentrate the light within a small cone, which may be directed to the lathe or other machine.

Globes of glass or translucent material are also designed in different shapes and contours to disperse the light broadly or narrowly, according to the specific needs. An illuminated diffusing surface sends out light in all directions according to Lambert's law; the relative intensity is proportional to the cosine of the angle between the direction of emission and the normal. Thus, an enclosing globe may have a large, curved bottom area and short sides, or vice versa, and will accordingly distribute more light downward or horizontally.

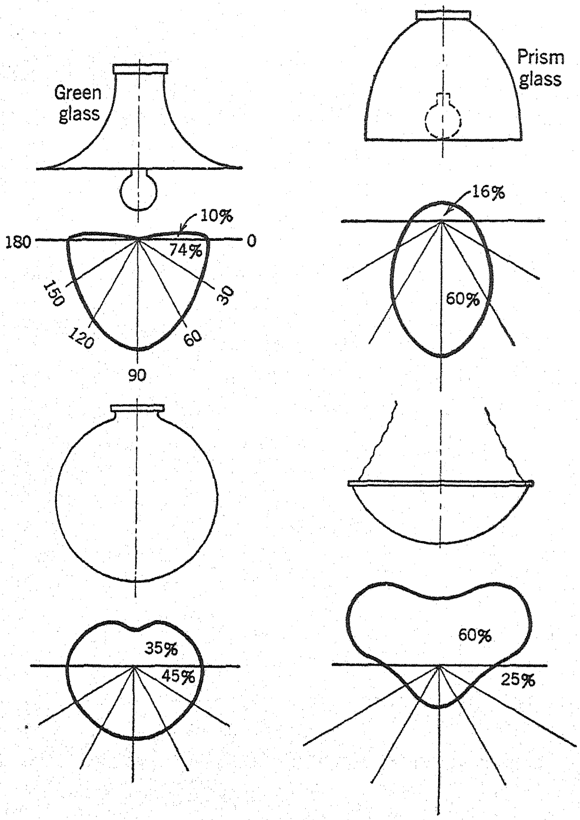

Fig. 23. Some typical reflectors and diffusing globes with their distribution curves. The radial distance to the distribution curve measures the relative illumination in that direction. Indicated percentages refer to the upper and lower hemispheres, respectively.

Combinations of reflectors and globes or reflectors of glass are often useful; these may be further modified by the employment of prisms of various shapes and sizes designed either to focus and concentrate the light in a downward beam, or to distribute it broadly. A few typical luminaires, with their associated light-distribution curves, are shown in Figure 23.

INTRINSIC BRIGHTNESS. Frosted lamp bulbs and the larger diffusing globes also reduce the intrinsic brightness of the source. Consider, for example, a bare tungsten filament. Its total output in lumens comes from an exceedingly small area and produces a blinding glare. This same total light distributed fairly evenly over the surface of the frosted bulb yields only a fraction of the same brightness (which, it may be recalled, is measured in the unit, candle power per square inch); and the brightness is still further reduced if the lamp is enclosed in a diffusing globe.

A 100-watt Mazda C lamp, with frosted globe, has a projected area, when viewed horizontally, of about 5 square inches. The frosting is not quite heavy enough to diffuse the light perfectly. If it were, the intrinsic brightness would be of the order of 20 candle power per square inch. Actually the diffusion is largely by internal reflection, and the bright area of the lamp appears to be a circle about 2.5 square inches in area. The intrinsic brightness therefore is about 40. If now this lamp be enclosed in a diffusing globe having a diameter of 9 inches (projected area 63 square inches), the brightness, if total transmission is assumed, will be reduced to 1.6.*

Intrinsic brightness above 3 candles per square inch should never be viewed directly for any period of time; within the line of sight brightness below one is preferable. The influence of brightness in the production of glare diminishes rapidly with increasing angle of incidence. At 15 degrees from the line of vision it is half what it is at 10 degrees.

GLARE AND SHADOWS. Glare is the limiting case of poor distribution in one direction just as shadows are in the other. The eye works most comfortably under conditions of reasonably uniform illumination. It adapts itself to the medium condition. With too great contrast within the field of vision, adaptation is to the brighter area, or else it wavers between the two, causing confusion and fatigue. In the presence of excessive brightness, glare in the usual sense, the eye is unable to function and is pained or injured.

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* For simplicity in computing brightness we may rate the Mazda C lamps at 12.5 lumens per watt, and, since one candle power is equivalent to 12.56 lumens, it is convenient and sufficiently accurate to allow one candle power per watt.

Glare is a somewhat complicated physiological effect but basically, it is *excessive contrast.* One area of the field is so intensively illuminated that response of the retina spills over to adjacent areas which become *blinded.* A more common and less appreciated effect is that of marked inequality of illumination. Reading under a good light in an otherwise dark or dimly lighted room throws an unnecessary burden on the adjustment mechanism of the eye and causes eye fatigue.

Partial shades and shadows are unavoidable under any condition of illumination, and their elimination would be wholly undesirable. It has been noted previously that the two-dimensional image on the retina is perceived in its true three-dimensional aspect with the help of shadows. On the other hand, sharp and contrasting shadows are disturbing. Like glare, they confuse the eye in its adjustment to the brightness of the picture, and they also produce false impressions of perspective.

A sharp shadow results from single-point illumination. The greater the number of light sources contributing to the illumination of the individual desk, the less distinct the shadows. The limiting situation is one of diffuse illumination coming wholly from illuminated walls and ceilings by reflection. This is *indirect illumination,* as exemplified in the opaque inverted reflector placed under the light source directing all the light upward. The *semi-indirect* luminaire achieves this result to a considerable extent. By diffusing some light downward, however, it reduces the excessive contrast between upper and lower hemispheres and produces a more pleasing effect.

STEADINESS. Steadiness, as contrasted with flicker and pulsation, is an important quality of light in illumination. It represents an even distribution of the light in time. It has been noted that the eye is capable of adjustment to a wide range of light intensities but this adjustment is a rather slow process—a matter of seconds. Effective ocular adjustment cannot be made to sudden fluctuations.

Flicker generally consists of an intermittent series of variable fluctuations: variable both as to time distribution and intensity distribution. It might be compared with a rattle in sound effects. In electric lamps flicker may result from variations in line voltage, due perhaps to the intermittent operation of an elevator motor on the same line; to an imperfect transformer; or, very commonly, to a worn-out lamp or a loose lamp-socket connection.

It is noticeable, for example, on subway trains where the current is supplied through a sliding connection against the third rail. Reading under such a light quickly fatigues the eyes. For continuous work, such as industrial occupations, flicker is exceedingly undesirable.

THE STROBOSCOPIC EFFECT. Continuous and rhythmic variations in intensity, of short period, constitute the stroboscopic effect. The eye has a certain lag, in relation to the light stimulus, by virtue of which it carries over an impression for a brief period. If the cycle of variation is sufficiently short, this carry-over blends one impression with the next, and the effect is one of steady illumination. It is by means of this ability of the eye to carry over, this so-called *after effect,* that we see the closely spaced, successive, still pictures on the moving-picture screen as a continuous picture in motion. If the spacing is not so close, a definite flicker is appreciated.

An incandescent lamp, operating on a 60-cycle current, passes through 120 semicycles a second, during each of which the voltage varies between zero and a maximum, and the temperature of the filament, from minimum to maximum. The filament has a lag in heating and cooling, which reduces the variation considerably, and the after effect of the eye is able to carry over this short cycle of moderate variation so that it sees a continuous and uniform flux of light.

Some of our subways operate on 40 cycles. The after effect is insufficient to carry over this longer interval, and a distinct and rather disturbing flicker is noted. The effect is intensified by the longer period of near-zero current and the consequent greater variation in the temperature of the filament.

Lamps of the neon type, having only gas as the incandescent element, go completely black 120 times a second. This causes a stroboscopic effect, especially noticed when the eye moves rapidly. A moving object appears to move by a series of jerks. This sensation becomes distracting and annoying during reading. It is to be avoided as far as possible.

The fluorescent tubes are also gas-filled. Their light is decidedly stroboscopic. It also has a novel stroboscopic effect related to color emission. The apparent whiteness of the light is due to a blending of several colors, each emitted by a single phosphor in the mixture with which the tube is coated. These phosphors react at different speeds on excitation by the ultraviolet light, and their luminescence dies out at different rates during the succeeding period of darkness. The result is a rapid succession of color changes. These stroboscopic effects are greatly reduced in installations of two or more lamps in parallel provided with electric devices which throw the separate circuits out of phase.

LIGHTING SYSTEMS

One of the essential details in the preparation of plans for a building is the design of its lighting system. Lighting, like ventilation, becomes more of a problem with increasing size of the structure. It too has its special requirements based on the proposed use of the building or of its component parts. In planning for lighting, whether it be the lighting of the home, the school, or the workplace, the facts and principles that have been discussed in the preceding sections will be found to apply.

At this point, however, we take note of the essential differences between natural (daylight) and artificial lighting systems, differences not particularly stressed heretofore because the essential principles are basic to both.

ARTIFICIAL LIGHTING DESIGN

Even in those places where the chief reliance is placed on natural lighting (such as schools), an auxiliary system of artificial lighting must be installed for use on dark days or during late or evening hours. Artificial lighting is therefore the system of major usefulness. It is also the one in which the major efforts have been made toward scientific improvement and adaptation to the needs of the occupants. Daylighting is accepted and some small attention has been paid to securing its maximum benefits, whereas the electric lighting industry of the present day represents an enormous volume of research and engineering development, to say nothing of capital investment. This in turn has led to standardization of lamps and units (luminaires) and to a great simplification of lighting design.

A Typical Design Problem. Let us now lay out an artificial lighting system for the classroom sketched in Figure 24. We will specify an average illumination at the working plane—the desk top—of 10 foot-candles. This is sufficiently generous to allow for some unavoidable irregularity in lateral distribution, although that point must be checked before the final plan is selected.

If we recall that one foot-candle of illumination is equivalent to one lumen of light incident upon one square foot we see that the total requirement upon the working plane of 690 square feet will be 6900 lumens. These are *net* or *effective* lumens actually utilized. It will be necessary then to determine the *effective utilization* of the luminous output of the lamps: that is, the fraction of the total lumens which can be converted into illumination under the existing room conditions.

THE UTILIZATION FACTOR. The room dimensions, the height of the luminaires above the working plane, and the reflection characteristics of the room, as well as the type of reflectors and diffusing globes employed, all enter into the determination of an over-all factor known as the *utilization factor*.

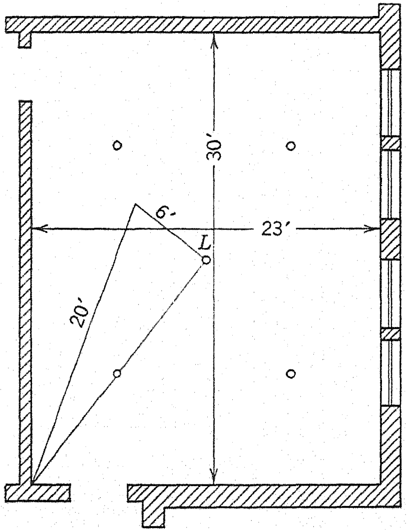

FIG. 24. Layout of artificial lighting system for a classroom.

The *room index* relates to the geometrical layout. The larger the room, the more effective is the utilization of the light. Consider a square room illuminated in any given manner. Now let this become the central area of a block consisting of 9 such areas each similarly illuminated. The central area now loses the benefit of reflection from its own walls but gains what would have been reflected from those of the other areas. If the original walls had been perfectly reflecting mirrors, the room would have *appeared* to be surrounded by other rooms equally illuminated and the reflected light would have been about the same as that now actually received from those others. This is obviously more light than would have been reflected from ordinary walls.

The shape of the room, as well as its size, and also the height of the lighting fixture above the working plane, enter into the utilization factor. The relations of these three variables are formulated as a *room index* as follows

$$\text{Room index (R.I.)} = \frac{2W + L}{6H}$$

in which W, L, and H are the width and length of the room and the height of the fixture above the working plane, respectively.

In the classroom it will be desirable to hang the fixtures 6 feet above the desk-top level to avoid direct glare. The room index will then become

$$\frac{2 \times 23 + 30}{6 \times 6} = 2.1$$

The *reflection characteristics* of the room; color of the walls and ceiling (as modified by dirt); interference by beams, belting, and shafting; extent of nonreflecting surface (such as windows and blackboards) are summed up in three general classifications as follows:

Good: clean white walls and ceilings, normal extent of window and door openings. No other interference.
Medium: ordinary light walls, somewhat soiled. Moderate interference.
Poor: dark or dirty walls, much machinery or other interference.

Our classroom will be assumed to have good reflection characteristics except for the rather excessive area of windows and blackboards. We may classify it as medium. The *utilization factor* is based on type of luminaire, room index and the reflection characteristics. The values in Table 23 will cover most situations and are as detailed as the general reliability of this procedure justifies.

TABLE 23

TYPICAL UTILIZATION FACTORS (globe diffuser)

Room Index	Reflection Characteristic		
	Good	Medium	Poor
1	0.42	0.38	0.35
2	0.52	0.49	0.45
5	0.62	0.58	0.55

Thus, it appears that just about one half the total luminous output of the lamps will become effective illumination at the desk-top level. The total requirement, therefore, will be

$$2 \times 6900 = 13{,}800 \text{ lumens}$$

The distribution of the light about the room must next be considered. A total of 13,800 lumens derived from one luminaire at the center of the room would provide the required average illumination, but the light would be badly concentrated near the center of the room. As a rough measure of the uniformity of distribution of the light over the working plane, we may take the ratio of the light intensity at two points: one directly under the luminaire, and the other in the farther corner.

With one central luminaire the distance to the point directly underneath would be 6 feet, and to the farther corners, about 20 feet. The inverse-square law would result in a ratio of intensities of 400 to 36 or 11.1 to 1, and the cosine law would introduce a further factor of 20 to 6 or 3.3 to 1, giving an actual ratio of 37 to 1. This refers, of course, only to the direct illumination; the reflected light would be similarly affected, but to a lesser extent.

Four luminaires, symmetrically spaced, would yield a similar ratio (over-all) of 5.5 to 1. Each of these, taken alone, will illuminate its nearest point 6.6 times as brightly as its near corner, but each of these points receives light from the other three luminaires, and this tends to even the general distribution.

The shape of the room suggests an arrangement of five luminaires such as is indicated in the sketch. This gives a distribution ratio, as between the brightest spot, now the center, and a corner, of 3.7 to 1 for the direct light. Reflection improves this to a considerable extent.*

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* A simple graphic method of computing the contribution of each luminaire to the illumination of a given spot is illustrated in Figure 24. On a scale drawing of the room connect luminaire *L* to the spot under investigation, say, the corner. Erect a perpendicular to this line at *L*, its length scaled to represent the height of the luminaire above the working plane (6 feet). The hypothenuse scales 20 feet, the direct distance from the light source to the corner at desk level. The relative light intensities, in the corner and directly under the lamp, taken on a normal surface, are, by the inverse-square rule,

$$\left(\frac{6}{20}\right)^2$$

(*Footnote continued on next page.*)

The required total of 13,800 lumens divided among five lamps gives 2760 lumens per lamp. If 15 lumens per watt are allowed for the larger Mazda C units, this gives 184 watts per lamp. Some excess will be provided by 200-watt lamps, therefore, but it is customary to allow for losses in the diffusing globe and for deterioration of the lamp, so that 250-watt lamps would be used. Some gain may be had from the use of globes designed to send more than half the light downward.

An actual installation of exactly this sort in the classroom shown in Figure 24 gave the following illumination as measured at the desk tops.

	Foot-Candles
Under center luminaire	14
Under side luminaire	12
Corner	8
Average of readings at tops of 35 desks	10.9

With these data a rough check can be made of the influence of reflection in a classroom with rather large window and blackboard areas. The diffusing globe used in this instance is shown in Figure 23 (lower left). It directs 45 per cent of the total lumens into the lower hemisphere where it is rather uniformly distributed. The illumination downward will then be

$$0.45 \times 250 \text{ watts} \times 15 \text{ lumens per watt} \div 12.56 \text{ lumens per candle power or } 135 \text{ candle power.}$$

At 6 feet this will yield $135 \div 6^2 = 3.7$ foot-candles.

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and the cosine relation is

$$\frac{6}{20}$$

so that the ratio of effective illumination on the horizontal surfaces becomes

$$\left(\frac{6}{20}\right)^3 = 0.027$$

This operation is repeated for the effect of each light source at the point in question. The values, totaled, give the total *direct* illumination at that point, in terms of the illumination received from one light source directly below it.

The direct effective illumination from each of the other four fixtures, distant 13.5 feet from the desk level at the center, will be

$$\left(\frac{6}{13.5}\right)^3 \times 3.7 = 0.325 \text{ foot-candles}$$

or, for the four, 1.3 foot-candles. The total estimated illumination at the central point, therefore, is 5 foot-candles as compared with the measured value, 14. Some 9 foot-candles, or nearly two thirds of the total illumination, apparently represent reflection from the walls and ceiling.

This reflected light is more evenly distributed than is the direct light because much of it comes from the walls. It was previously estimated that the direct illumination of the corner would be 1/3.7 of that at the center, or about 1.37 foot-candles. It actually measured 8 foot-candles of which 6.65 must come from reflection. This value, compared with the 9 foot-candles reflected to the center position, indicates the greater uniformity of distribution of the reflected light.

INTRINSIC BRIGHTNESS AND GLARE. Finally, the type of *diffusing globe* and its *height* above the desk top remain to be decided. It was tentatively assumed, in getting the room index, that the lamps would be 6 feet above the desks. With the arrangement of luminaires finally adopted, a line from the eye of a pupil in the rear of the room to the front light makes an angle of 10 degrees with the horizontal. This is the worst position in the room from the point of view of possible glare, and the 10-degree angle from the line of sight is about the minimum permissible.

A 12-inch globe has a projected area of 113 square inches. In computing intrinsic brightness it is convenient and sufficiently accurate to allow one candle power per watt so that the brightness of the surface of the globe would be

$$\frac{250}{113} = 2.2 \text{ candles per square inch}$$

At 10 degrees from the line of vision such a brightness would not be intolerable, but in this situation a 15-inch globe would be recommended, reducing the brightness to 1.4 candles per square inch. If the plane of the lamps is raised 2 feet, the angle of vision would become 15 degrees, and the influence of brightness, as noted previously, would be reduced one half.

Shadows. In this design the possibility of objectionable shadows is eliminated by the employment of five luminaires and the considerable proportion of indirect (reflected) light. In a smaller room at least two luminaires would be required to prevent shadows, unless greater advantage is taken of ceiling reflection, as is done in some of the modern reading lamps of the semi-indirect type.

Lighting the Home. Home lighting is both utilitarian and aesthetic. Happily the *soft* lighting effects, suggestive of quiet and relaxation, are also favorable for vision. Perhaps this, too, is adaptation; an instinctive appreciation of the value of the medium. The artistic and the restful however must not be overdone. The "dim religious light" of the cathedral well serves its purpose, but it is better suited to contemplation than to reading.

Individual reading lamps, well placed with reference to the reader's position, preferably above and to one side, provide good reading conditions. The popular semi-indirect type of reading lamp gives some direct illumination, but most of its light goes to the ceiling. This reflected light gives an excellent shadowless effect with broad dispersal, serving two or more readers.

For the remainder of the house, lighting should be even more utilitarian. The powerful 150 or 200-watt lamp in the center of the kitchen ceiling, well protected by a diffusing globe, with one or more shielded side fixtures, where most needed, actually does "make work lighter" to quote an advertisement. This is good treatment for the bathroom, also, while the bedroom is best served by the opposite arrangement, low-intensity general lighting with special fixtures for the dresser and bureau and perhaps a reading lamp on the head of the bed.

In brief, a convenient, comfortable, and pleasing arrangement is the best specification.

Industrial Lighting. The lighting of industrial establishments introduces certain new problems. The first of these is the matter of local requirements as distinct from over-all illumination. In a large machine shop, for example, it might prove unduly expensive to provide general illumination, such as was provided in the classroom, of suitable intensity for the individual job. This is especially true when the work itself—perhaps fine machine work or inspection—calls for a rather high intensity of light. The desired result is achieved by local spotlighting, superimposed on a general lighting of lower intensity.

The local luminaire is usually an enclosing reflector which projects the light as a beam and protects the eyes of the worker and others against glare. By this means it is possible to produce illuminations of 50 to 100 foot-candles if needed on the work. It is not wise, however, to produce too great a difference between local and general or background illumination. A ratio of not over 20 and preferably 10 or less has been recommended.

High ceilings, with the overhead space obstructed by pipes, shafting, and belting, provide a minimum of reflection from above, so that factory lighting is usually best accomplished with the use of completely reflecting luminaires which illuminate only the lower hemisphere. This arrangement greatly increases the intrinsic brightness of the source and requires either larger diffusing globes or the use of smaller lamps more closely spaced. Shadows, too, are highly undesirable in most industrial occupations, and these are minimized by the more closely spaced units.

Economy in lighting is also a special feature in the factory layout, a feature to which little or no attention has been or need be given in the school, small office, or home. For this reason industrial establishments have been quick to realize the advantages of the gas lamps. The *Cooper–Hewett* mercury arc, the blue tube often seen in photographer's windows, was the earliest of these to receive commercial attention. It has been employed extensively in the Federal Post-Offices and in many large factories where a light of uniform high intensity is desired over the whole room.

The *fluorescent lamp,* the Mazda F type, is a later development. It overcomes the chief objections to the mercury lamp, monochromatic light and color distortion, and produces 30 to 60 lumens per watt, two to four times as much as the Mazda C lamps. The shortcomings of the fluorescent lamps have been discussed, but the advantages of economy and coolness and their artistic possibilities lead one to suggest that, with the inevitable improvements that will result from their further study and wider use, they will become the light of the future.

NATURAL LIGHTING

The maximum utilization of daylight in buildings requires careful architectural planning and involves certain added construction and maintenance costs. These requirements may partially offset the manifest advantages of natural lighting. At least they have not been overlooked by those whose studies have been in the field of electric lighting and who have even prepared cost sheets to prove its economic advantage over daylight.

Natural lighting, however, still has its champions, and sanitarians, in particular, will be the last to consent to the *windowless home* which has been suggested. The recommendations of the Committee on the Hygiene of Housing have been quoted earlier in this chapter. Abundant window areas with the maximum possible direct and unobscured exposure to the sky and the sun make for human well-being, both physical and mental. Despite our present-day reliance on electric lighting and the enormous advances that have been made and that continue to be made in its utility and economy, there is still something in the advocacy of daylight and sunlight in the home which cannot be expressed in terms of lumens per watt.

COMPUTATION OF NATURAL LIGHTING. Natural lighting is derived either directly from the visible sky area or by reflection. Computations are usually based on the sky area alone, but it is apparent from the outdoors view that much light comes to the room by reflection from light-colored objects. Within the room, reflection plays a much more important part than it does in artificial lighting because of the limited distribution of the initial light.

The great variability of the sky brightness itself makes it rather hopeless to attempt any such design computation as was carried through in the preceding section. We cannot expect to meet any specified lighting requirements with natural light; auxiliary systems of artificial lighting must be provided if the room is to be adequately illuminated during all hours or even during daylight hours on cloudy days. Specifications for natural lighting call merely for the maximum economic utilization of this beneficent natural resource. It becomes, then, largely a matter of architectural arrangement, especially of the natural *luminaires,* the *windows.*

With a given window arrangement, the basis for computing the *direct* illumination—the amount of light that will enter the window—is the brightness of the sky in the direction of exposure, and the extent of visible sky area as determined by obstructions outside and by window size and arrangement and room dimensions within. Much of this direct light is reflected within the room and contributes to the general illumination. The reflection characteristics of the room, previously discussed, therefore enter into the computation of natural lighting.

Sky Brightness. If a photometric measurement be made of the light that passes through one square inch of opening exposed to the clear or slightly overcast sky, the result may range from 1 to 4 or more candles, depending on the sky condition, hour of the day, and direction of exposure. This is the sky brightness in candles per square inch.

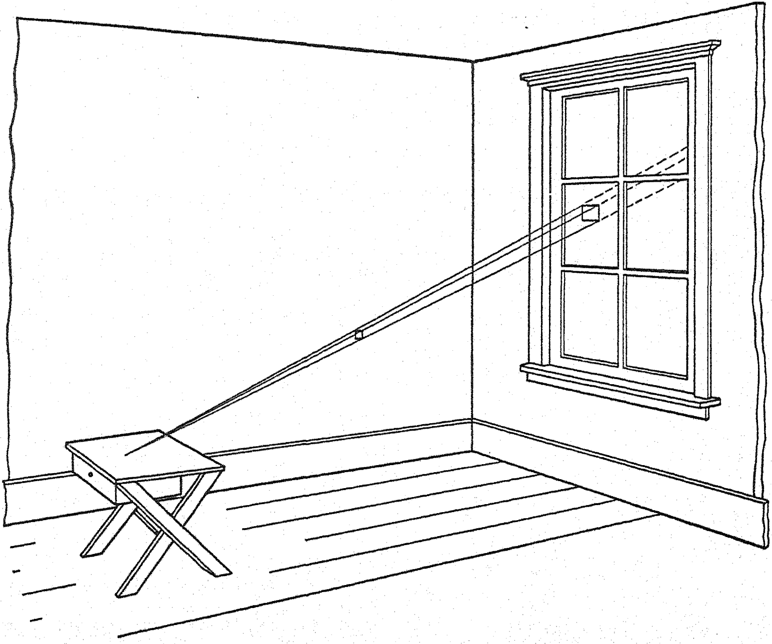

Fig. 25. Relation of sky brightness to natural illumination.

It may appear that we have not measured an inch of the sky, but intrinsic brightness is invariable with distance. If we think of the sky as a bright wall at some specific distance, we see that the same amount of light would pass through a 1-inch-square opening whether the sky be 1 mile or 10 miles away. Regarded as a source of light, a square inch of sky view, measured on the window, represents just as many candles as the recorded sky brightness.

Furthermore, it makes no difference where the inch opening is located with reference to the position of the observer. From the rear of the room a 1-inch opening halfway between the observer and the window, Figure 25, may register, say, 2 candles (sky brightness 2 candles per square inch). This opening will coincide with an area of 4 square inches at the window having the same sky brightness, 2 candles per square inch, or 8 candles total. But the application of the inverse-square rule will equalize these two values when referred to illumination at the point of observation.

NUMERICAL VALUE OF SKY BRIGHTNESS. Sky brightness depends largely on cloudiness. A moderately overcast sky, one with bright white clouds, has a greater brightness than the clear blue sky; darker clouds reduce the brightness materially. Over cities the brightness of the sky is reduced by smoke and the associated haze and, near the sea, by fogs.

Sky brightness is also a function of the latitude and altitude of the place, of the season and hour of the day, and of the position of the visible area with respect to the position of the sun.

Table 24 shows the average brightness of the whole clear sky, in the United States, as affected by some of these factors.

TABLE 24

AVERAGE BRIGHTNESS OF THE WHOLE CLEAR SKY IN THE UNITED STATES*

Area	Latitude	Sky Brightness (Candle Power per Sq Ft)			
		June 21		Dec. 21	
		Noon	8 a.m. or 4 p.m.	Noon	8 a.m. or 4 p.m.
A	30	476	280	350	181
	36	491	290	330	176
	42	496	313	311	119
B	30	554	335	393	241
	36	532	324	366	214
	42	526	338	359	160
C	36	586	365	404	265
	42	565	370	395	172

A—States bordering the Atlantic Ocean; elevation from 0 to 500 feet.

B—Plain States lying between the Mississippi River and the Rocky Mountains; elevation 1500 to 2000 feet.

C—Plateau States lying between the Rocky Mountains and the Sierra Nevada and Cascade Mountains; elevation about 7000 feet.

*Abstracted from a more extensive table computed by J. E. Ives et al., *U. S. Pub. Health Service, Pub. Health Bull.* 218, 1935, from the original observations of H. H. Kimball, *Monthly Weather Rev.*, U. S. Weather Bur., 47, 769, 1919

THE SKY PICTURE. The view through the window from any point P within the room may show a certain area filled with trees or buildings and another area of unobstructed sky. This sky picture may be outlined on the window pane and measured (in square feet).

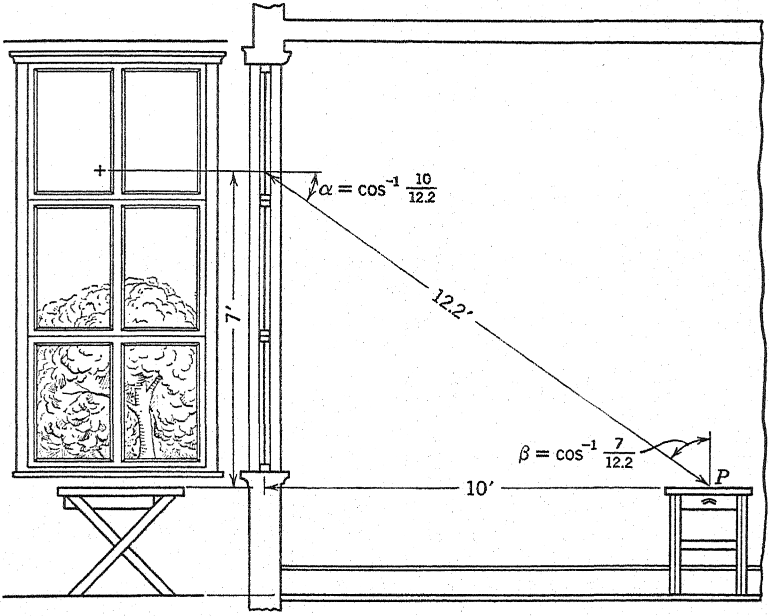

FIG. 26. Direct illumination from the sky on desk in front of and below window.

The point P is below and usually to one side of the center of the sky picture; that is, the line of vision through the window makes an angle α with the perpendicular to the window. The *apparent* area of the sky picture from P is therefore the area measured on the windowpane times cos α.

In the situation illustrated in Figure 26, the window area is reduced in the ratio 10/12.2. Generalizing, to include such an aspect as is presented in Figure 27, we find that the reduction factor, cos α, at point P is

$$\frac{\text{Perpendicular distance to wall in plane of window}}{\text{Direct distance to window}}$$

Direct Illumination. The illumination at P, due to the sky, is now obtained just as it would be from an artificial light source. The total candle power is the sky brightness times the reduced window area. This is further reduced by the inverse-square law, which allows for the distance from the window, and by the cosine law, which corrects for the angle of incidence on the horizontal desk top. This entire computation may be formulated as follows (see Figure 27):

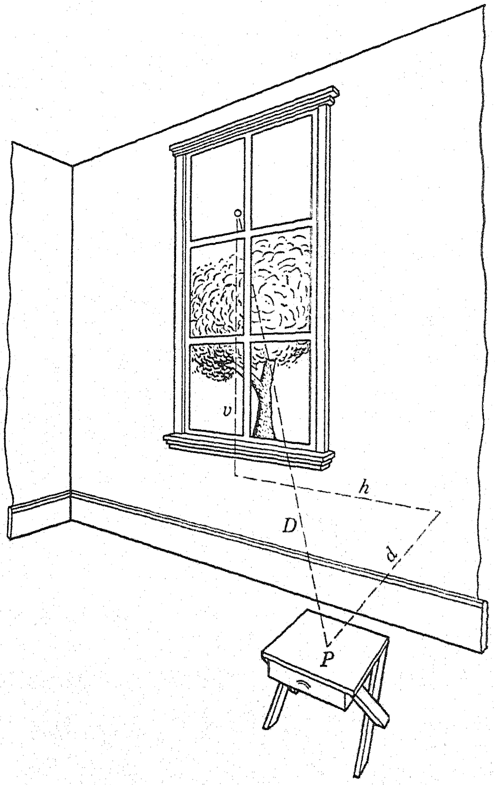

Fig. 27. Direct illumination from the sky on desk to one side of and below window.

Let A = area of sky picture from P measured on windowpane
B = sky brightness (in same unit of area as A)
d = perpendicular distance from P to wall

h = horizontal distance from foot of d to point vertically under center of sky picture

v = vertical distance from h to center of sky picture

D = direct distance P to center of sky picture

Then

$$(D^2 = d^2 + h^2 + v^2)$$

The apparent area at P is

$$A \cdot \frac{d}{D}$$

and the total intensity of light at the window, in the direction of P,

$$A \cdot B \cdot \frac{d}{D} \text{ candles}$$

This is also the illumination, in foot-candles, on a surface normal to the incident light and one foot away from the window.

Reduced by the inverse-square law, this becomes

$$A \cdot B \cdot \frac{d}{D} \div D^2 = AB \frac{d}{D^3} \text{ foot-candles}$$

on the normal plane at P and, by the cosine law,

$$A \cdot B \cdot \frac{d}{D^3} \times \frac{v}{D} = A \cdot B \cdot \frac{dv}{D^4}$$

foot-candles on the horizontal desk top.

This computation is somewhat simplified by the direct measurement, at P, of the *square degrees* of sky exposure. This requires special optical equipment, the simplest form of which is a convex mirror on which the area of the reflected sky image is measured by means of a co-ordinate grid ruled on the surface. The size of this image is obviously correctly reduced for distance and angular aspect just as would be the image on the ground glass of a camera.

REFLECTION. The foregoing computation is for direct sky lighting. Its chief interest lies in the principles that it illustrates but it does establish a point of departure for a further investigation of natural lighting. The illumination of a room is always greater than that obtained by direct sky exposure. This point has been covered in the discussion of artificial lighting. The reflection characteristics of the room itself determine how well that light which enters is utilized and converted into illumination.

The value of reflection in a classroom has been demonstrated and measured in an experimental room constructed especially for the purpose.* In this room the window area could be manipulated at will as to width, and it extended up to the ceiling which was itself movable between 6 and 12 feet in height. Measurements could be taken with white walls and ceilings (reflection factor 78 per cent) or with either or both completely blackened.

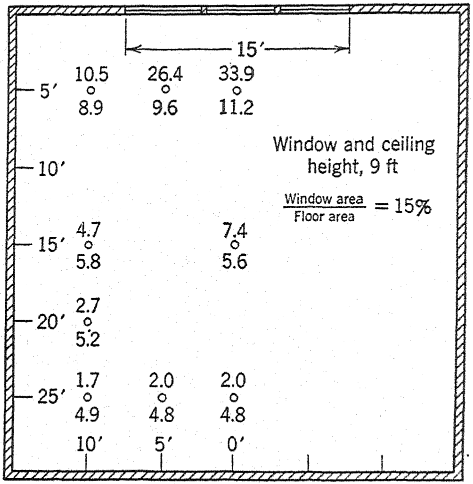

FIG. 28. Natural illumination in experimental room.

Upper values at each station, direct illumination (foot-candles) in room with black walls and ceilings.

Lower values, reflected illumination (gain with white walls and ceilings), (Ives' data).

Some of the pertinent data are reproduced in Figure 28, which shows a plan of the room. The floor area was 30 × 30 feet. For this experiment, the ceiling and window height was 9 feet (above the desk-top level of 40 inches), and the window width, 15 feet, in one centrally spaced opening. The ratio of window to floor area was 15 per cent. Twenty-five observation points were established in rows and columns on 5-foot centers.

All values are referred to a standard sky brightness of 100 candles

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* J. E. Ives, *loc. cit.*

per square foot (0.695 candle per square inch). This value was adopted merely as convenient basis of reference. Actual illumination within the room will vary directly with the brightness of its source (see Table 24).

The International Commission on Illumination has proposed a standard sky brightness, for reference in building design, of 159.1 candles per square foot. This supposedly represents conditions in Great Britain during dull weather. For the United States a standard value of 217.1 has been suggested as more representative of cloudy weather here. With this value the illumination in the room would be more than twice the values shown.

Under the conditions illustrated, about one fourth the total illumination at the desk immediately in front of the window came from reflection; in the rear corner, 75 per cent of the total was reflected.

DISTRIBUTION. The distribution of the daylight about the room is customarily measured by the ratio of maximum to minimum values of the illumination on individual desk tops. Usually it is planned to keep this ratio at four or less. In the classroom shown in Figure 24, with artificial light the ratio was found to be 14 to 8 or 1.75.

Under natural illumination, in the experimental classroom with a window area equivalent to 15 per cent of the floor area and other conditions rather ideal, the ratio was 45.1 to 6.6 or 6.85. The square room was not well designed as a classroom. A useful rule is to have the width (from the window wall) not greater than twice the height of the window top above the working plane or desk-top level: 18 feet in this instance. The corner desk at 20 feet from the window had an illumination of 7.9 giving a distribution ratio of 5.7. This would be materially improved if the rear wall had been only a few feet from this desk rather than 10 feet. Windows, in all cases, should extend to the ceiling, and the higher the ceiling the better the utilization and distribution of the light. With a constant ratio of window to floor area the higher window (at the expense of width of openings) gives a better sky picture and a more advantageous angle of incidence in the rear of the room.

MEASURES OF DAYLIGHT UTILIZATION. In addition to its dependence on sky brightness, the natural illumination within any room is influenced by the amount of sky visible, the size and arrangement of the window openings, the size and shape of the room and its reflection characteristics. All these except sky brightness are matters of design and maintenance and may be regarded as fixed in any given situation. It is useful, therefore, to establish some measure by which these factors of daylight utilization may be evaluated.

A simple measure is one which relates the observed sky brightness at the time to the resultant illumination at the darkest desk in the room. In the room illustrated in Figure 28, for example, the rear corner desk had an illumination of 6.6 foot-candles with a sky brightness of 100 candles per square foot. This relation is fixed by the room factors only.

A similar measure, and one more readily applied, is the ratio between illumination at the far corner and illumination at the outer window sill from an unobstructed half of the sky dome; or, on the roof, from the whole sky dome. A uniform sky brightness of 100 candles per square foot will yield a window-sill illumination (one half the sky exposed) of 157 foot-candles.*

No extent or arrangement of window area can provide illumination in the absence of daylight. Actual measures of the illumination on the desk tops are of only momentary interest as suggesting the need at the time, of auxiliary lighting. The utilization measure, on the other hand, indicates to what extent the available skylight is being utilized within the room. Perhaps it may be improved by window cleaning or by interior cleaning and painting. The utilization measure also provides a basis for the study of design of window arrangements and room dimensions.

Classroom Design. It is desirable, for example, that a classroom, with windows on one wall only, shall be oblong in shape, with the window wall on the long side and at the left of the pupils when seated. Windows should extend to the ceiling, and the total window area should be not less than 15 per cent and preferably should be 20 per cent of the floor area. In rooms wider than 20 feet this ratio should be increased up to 25 per cent.

The most poorly illuminated desk should have an illumination of not less than 2 per cent of the illumination from a half sky on the

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* The theoretical relation between sky brightness B in candle power per square foot and the illumination E of a horizontal surface exposed to the whole sky dome is

$$E = \pi B$$

This relation accounts for the odd value for standard sky brightness 159.1, referred to previously. A standard illumination of 500 foot-candles from the whole sky dome was actually adopted; equivalent to 159.1 candle power per square foot of sky brightness.

window sill. This provides a minimum illumination of 3.14 foot-candles at a sky brightness of 100 candles per square foot, or about 7 foot-candles for a normal clear sky. For comparison, note that the window arrangements shown in Figure 28, which are not at all ideal, provided a minimum illumination (rear corner desk) of 6.6 foot-candles at a sky brightness of 100 candles.

The inner row of desks should not be farther from the window wall than twice the height of the window top above the desk tops. Ceilings should be white, and walls light-tinted, except for a somewhat darker band extending from the floor to about 30 inches above the desk tops and about and above the blackboards. This is to reduce the intensity of direct reflection in the line of vision.

THE HOME, OFFICE, AND SHOP. Industrial and commercial establishments, in general, depend largely on artificial light. If natural light is utilized in offices and similar places, the conditions and requirements are not different from those outlined for the classroom. Natural lighting in the home, however, is based on somewhat different considerations.

In the design of the dwelling, windows are not often planned with reference to illumination. Externally they are fitted into the general architectural plan; internally, and always secondarily, they are spaced with reference to pleasing arrangements and to the placement of furniture. Their usefulness as luminaires is then further reduced by covering them with shades, curtains, and overhangs.

These shortcomings are in considerable part overcome by the fact that the room occupant is free to choose the most favored position and that the desk or reading chair may be placed sufficiently near a window to obtain good illumination. Windows in the home, therefore, while failing to provide any such general illumination as is required in the classroom, do satisfy the requirements of adequate local illumination at a few chosen spots in the room.

In order not to lower the status of the window in the home unduly, we may perhaps, at the conclusion of our discussion of illumination, digress sufficiently to consider some of the varied functions of such a window. In addition to its usefulness in decoration, that is, contributing to a pleasing effect, the window meets two rather fundamental human needs. We are all of us more or less sun worshippers and to some extent, claustrophobes; that is we dislike being shut in.

We have already noted a good reason for our instinctive appreciation of daylight and sunlight in their bactericidal and therapeutic properties. This instinct leads to a certain degree of mental satisfaction and contentment. We "bask" in the sun, and our moods fluctuate with the sunniness of the day.

The "view" from the window, even if it be confined to some brick walls and a patch of smoky sky, also satisfies something rather deeply inbred. It not only rests the eyes engaged in close desk work, but also permits the mind and the personality to expand beyond the confining walls and all that they connote.

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CHAPTER 7

ATMOSPHERIC POLLUTION; NOISE

THE PROBLEM OF ATMOSPHERIC POLLUTION

Perhaps man's most extensive modification of his atmospheric environment has been the pollution of the atmosphere over the areas of great cities by the smoke, dusts, and gases which represent the by-products of industrial and community life. One gains a rather vivid impression of this, when, during a radio weather report one hears some such statement as "lowest temperature expected tonight, in the city 40 degrees, in the suburbs 35 degrees." This differential arises for the most part from the blanket of smoke and dust with which the city is covered which reduces the rate of reradiation of the day's accumulated warmth during the cooler hours of the night. It is the principle of the "smudge pot" of the orange grove applied to a great city.

The famous *fog disaster,* which occurred in the Meuse Valley in Belgium in 1930, is a striking example of gross atmospheric pollution resulting in widespread damage. Over a period of 3 days there were severe acute pulmonary attacks resulting in some 60 deaths. Cattle, birds, and even rats were killed. Various explanations, mostly designed to exonerate the industrial plants of the region, were offered. Some investigators attributed the disaster to sulphur dioxide; certain clinical evidence, later adduced, indicated fluorine poisoning resulting from the extensive use of fluoride in the steel industries, coupled with an unusual meteorological condition which precipitated a dense fog in the valley.

Investigations, made some years ago, disclosed a sufficient concentration of sulphur dioxide in the air, over a considerable area in Staten Island, N. Y., to cause much throat irritation and definite damage to garden crops. Conditions were worse during foggy weather with light winds from the direction of industrial plants, smelters, and oil refineries, several miles away in New Jersey.

EXTENT AND NATURE OF ATMOSPHERIC POLLUTION

The U. S. Weather Bureau at certain of its city stations makes an hourly reading of the Owens Automatic Recording Filter whereby the discoloration of a white surface by the dirt filtered from a fixed volume of air, the *shade number,* is employed as a measure of the *suspended impurity.* By calibration against known concentrations of such impurities, this shade number is translated to the unit, *tons of suspended impurity per cubic mile of air.*

The cubic mile unit does not mean that the pollution extends to that or any other definite upper limit. One ton per cubic mile is equivalent to 0.22 milligrams per cubic meter, a unit more suggestive of the actual situation disclosed by the test.

Suspended Impurities over New York City. The Weather Bureau data for New York City, over a period of 11 years, 1931–41, show a mean value of 1.22 tons of suspended impurities per cubic mile. Distributed among the months, mean values were:

November to March	1.32 tons
April to October	1.15 tons

The difference probably represents the influence of winter heating as compared with the industrial effect. If so, the heating of homes, stores, schools, and so on contributed about 13 per cent of the total pollution during the winter months.

Wind movement induces turbulence, a condition favoring the transport of more and heavier particles of impurity, and decreases the time interval between the point of pollution and the point of examination. These two effects tend to increase the pollutional load at higher wind velocities and thus to mask in part the opposite effect of simple dilution of a given amount of impurity in a greater air volume.

Coal Smoke and Soot Fall. A somewhat different measure of atmospheric pollution is the *soot fall,* the material that is deposited, as distinguished from that still suspended. There is little correlation between the two measures of pollution. They increase together with increasing pollution, but, with a given load and under varying atmospheric conditions, they are inversely related; the greater the deposit, the less the suspended load.

New York City. A study of soot fall in New York City* made during 1926 showed the quantities of total material and of certain characteristic constituents collected, as shown in Table 25.

This soot fall contained determinable quantities of ammonia and

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* S. Pincus and A. C. Stern, *Am. J. Pub. Health,* **27,** 321, 1937.

TABLE 25

SOOT FALL AT 14 STATIONS IN NEW YORK CITY, APRIL 1936
Tons per square mile per month (Pincus and Stern)

	Average All Stations	Maximum Station
Total solid matter	103	244
Water soluble	13	28
CS_2 soluble (tar)	1.3	4.7
Ash (on combustion)	59	148

sulphuric acid. Direct air samplings showed additional quantities of each of these in gaseous form.

ABATEMENT CAMPAIGN IN PITTSBURGH; BEFORE AND AFTER. Extensive and long continued studies of air pollution at Pittsburgh, once known as the "smoky city," were made by the staff of the Mellon Institute of that city, beginning in 1913. Smoke abatement measures were instituted, and in 1923–24 a resurvey was made employing similar analytical techniques and sampling from the same series of 12 stations about the city.

A summary of the comparative data reported is given in Table 26. The preventive methods were based upon an attempted limitation of periods of discharge of "dense" smoke. The only noticeable improvement is a decrease in the total quantity of tar collected in spite of an increase of more than one third in the total soot fall. That is, there was a marked decrease in the relative proportion of tar in the total deposit.

TABLE 26

SOOT FALL AT PITTSBURGH, PA., OVER AN 11 MONTH PERIOD
August to June, during 1912–13 and 1923–24

	1912–13		1923–24	
	Tons per Square Mile per Month	Per Cent	Tons per Square Mile per Month	Per Cent
Total	85	100	119	100
Fixed carbon	26	30.7	42	35.6
Tar	0.84	1.0	0.26	0.2
Ash	58	68.3	76	64.2

This shift is characteristic of the change likely to be observed following a smoke abatement program. The emphasis is placed upon *smoke*, and the abatement methods consist of better firing, higher temperatures in the combustion chamber, forced drafts, and other conditions leading to a more complete combustion of the coal. Emission of black smoke is materially limited and the tar and unburned carbon in the atmosphere correspondingly reduced, but there is no noticeable reduction in the quantity of total impurities discharged into the atmosphere.

London. Investigations of the air over London and certain other British cities have been made for a number of years, beginning in 1915, by the Advisory Committee on Atmospheric Pollution of the Meteorological Office, Air Ministry. A typical set of data is reproduced in Table 27, recomputed from the unit metric tons per 100 square kilometers, to tons per square mile.

TABLE 27

Soot Fall in London—Average Values for the Period April 1915 to March 1916 and April 1916 to March 1921, from 6 Stations and from the Stations Showing the Highest and Lowest Values in Each Constituent

Tons per Square Mile per Month

	Six Stations	Maximum Station	Minimum Station
Total soot fall	55	156	21
Water soluble	23	60	10
Ether soluble (tar)	0.5	1.2	0.2
Ash	37	108	14
SO_3	5.4	8.2	2.9
NH_3	0.4	0.8	0.2

The British investigators also made continuous hour-by-hour records of the suspended impurities. A conspicuous result was the high degree of correlation observed between suspended impurities and *fogginess* over London. The familiar *haze*, so characteristic of any view which extends for a mile or more over a large industrial city is a manifestation of the same phenomenon. The effect of atmospheric pollution upon *visibility* is treated in the section dealing with meteorological effects of atmospheric pollution (p. 174).

Gaseous Impurities. The combustion of certain of the commercial grades of bituminous coal may produce sulphur dioxide, which, uniting with aqueous vapor of the air, forms sulphurous acid. This is one of the most characteristic features of the smoky air of an industrial city by reason of the decided odor of "sulphur" and the unpleasant throat irritation.

Many industrial processes, especially those of the chemical industries, lead to the discharge of waste gaseous products. The numbers and varieties of these are so great as to defy any attempt at generalization. Confining our interest to the effects of these substances in the free air we may classify them roughly into:

Substances like sulphur dioxide having specific irritating effects.

Toxic substances like benzole and carbon monoxide.

Acid vapors and fumes, irritating and destructive of goods and structures because of their acidity.

Substances objectionable chiefly because of their odors.

The smelting of sulphid ores is accompanied by the liberation of sulphur dioxide, which under certain circumstances may cause serious injury to vegetation. This particular type of atmospheric pollution has been studied in certain of the Western states, in connection with extended litigation. At one of the larger smelters in California, about 748 tons of sulphur dioxide were being produced daily. Vegetation was injured within a radius of 9 miles, in the direction of the prevailing winds. Injured trees showed an increased sulphur trioxide content in the foliage.

INFLUENCES UPON HEALTH

We may now inquire what are the influences of these various, and at times considerable, modifications of the natural atmospheric environment upon human health and well-being. This question has frequently been answered off hand, and without scientific study, by such general statements as that Pittsburgh is characterized by a high pneumonia rate or that the general health on the smoky (poorer) side of the railroad tracks is inferior to that on the cleaner (wealthier) side. Such observations are without value.

Scientific inquiry seeks a more specific answer and has, in general, taken one of two major lines of approach; the effects of the inhalation of smoke and of the products of combustion, and the effects of suspended impurity in the air in the causation of fogs and the reduction of sunlight.

RESPIRATORY DISEASES. One certain effect of the habitual breathing of smoky air is a condition known as anthracosis of the lungs, defined as a deposit of carbon particles of extraneous origin, in the lung tissue. The relation of anthracosis to pulmonary diseases, however, appears to be uncertain.

Various authorities have shown, by statistical comparisons of groups classified as rural and urban, residents of towns engaged in textile manufacture and those in smoky cities, coal miners and non coal miners, and so on, that higher death rates from tuberculosis, bronchitis, pneumonia, and pleurisy, to say nothing of higher infant mortality and general death rates, are associated with the breathing of smoky or coal-laden air. Such data all suffer the common fault of comparing environments differing in other essentials than the one single matter of smoky atmosphere. Similar comparisons, for example, have shown equally valid distinctions in tuberculosis death rates, as between coal miners and others, but in these instances *in favor* of the miners.

The Pittsburgh studies showed a definite relation between smokiness and pneumonia deaths by city wards, which was somewhat independent of congestion of population, taken as an index of poverty. Even this, however, leaves many other possible factors to be dealt with. These same studies developed a clinical thesis that anthrocosis, by clogging the lymphatic system, interfered with the process of resolution essential to satisfactory recovery.

INTERFERENCE WITH SUNLIGHT. The effect of smokiness in obscuring *sunlight,* and especially the *ultraviolet* portion of the solar radiation, being subject to direct measurement, may be recorded with fewer disqualifying reservations. Photoelectric measurements of light intensity upon a horizontal surface made within the city and at some near-by place outside the influence of city smoke provides a satisfactory basis for an estimate of the total loss of light.

Measurements of this kind, made at Baltimore, Md., showed an average loss of light over an entire year, of 14.1 per cent. The loss was somewhat less on clear days, 13.2 per cent, than on cloudy days, 15.9 per cent. Losses on single days amounted to as much as 50 per cent. The losses were greater on humid days and decreased with increasing wind movement.

Similar studies of the *ultraviolet light,* the most germicidal portion of solar radiation, showed an average loss of about 50 per cent during the winter months and of 28 per cent in midsummer. Corresponding soot fall over the year (in tons per square mile per month) amounted to:

Total	150
Ash	67.6
Tar	0.72

The intensity of the atmospheric pollution varied inversely with the distance from the center of the city. The soot fall at a point 3 miles from the city hall was just half what it was in the center of the city, while at a point 10 miles away it was reduced to one fifth.*

Similar studies in Chicago † showed that the ultraviolet light received in the near-by suburbs during the winter months was over twice that received in the central "loop" section.

RICKETS. Rickets is a chronic nutritional disorder of the young in which the structure of the bones is altered, with enlarged extremities and softening, so that they bend under the weight of the body. It is well established that this condition can usually be prevented and generally cured by suitable exposure to direct sunshine; also by the administration of vitamin D. Ultraviolet light of certain wave lengths, when applied to certain sterols, found widely in nature and in small concentration in the human blood and skin, produces vitamin D. These same rays applied therapeutically are curative. Thus we have a complete cycle of evidence.

In the middle and northern latitudes, the natural ultraviolet radiation from the sun is greatly reduced by atmospheric absorption and dispersion during the winter months. This effect is aggravated and extended into the summer months by smoke and other suspended impurities. Rickets is a disease of the more northern latitudes, and of the winter season. It is more prevalent in cities than in the country.

DENTAL CARIES. Various investigators have found similar relations with respect to dental caries, perhaps the most common disease of the human race. Caries is intimately associated with calcium — phosphorus metabolism, and, like rickets, its incidence has been shown to be lessened by administration of vitamin D and by exposure of the body to ultraviolet radiation (artificial).

Like rickets, it too is a matter of latitude. More fundamentally, it is related to total hours of sunshine. East and Kaiser‡ have made a statistical analysis of the data collected by the U.S. Public Health Service, representing examinations of some 281,708 children living in 358 rural counties. Employing the methods of partial correlation, they found definite and significant association between dental caries

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* J. H. Shrader, et al, *Am. J. Pub. Health,* **19**, 717, 1929.

† F. O. Tonney, et al, *J. Preventive Med.,* **4**, 139, 1930.

‡ B. R. East and H. Kaiser, *Am. J. Diseases Children,* **60**, 1289, 1940.

and both sunshine and latitude, each taken independently. Some of their more important findings are reproduced in Table 28.

TABLE 28

Reduction in Dental Caries (Per Cent of Mean Rate for Each Group) Independently Associated with *Increase* in Total Hours of Sunshine, *Increase* in Mean Winter Temperature, and *Decrease* in Latitude (East and Kaiser's Data)

	Sunshine, 100 hr			Winter temperature, 10° F			Latitude, 1°		
Age group	6–8	9–11	12–14	6–8	9–11	12–14	6–8	9–11	12–14
Boys	7.4	3.9	5.2	3.6	2.7	6.0	2.7	4.1	5.2
S.d.	1.0	0.8	0.7	4.5	3.8	3.5	1.3	1.1	0.9
Girls	6.3	4.7	5.5	10.7	3.2	16.7	1.1	4.2	6.1
S.d.	1.6	1.0	0.6	4.3	3.3	2.8	1.2	0.9	0.8

S.d.—standard deviation of the result. A result not less than twice its own standard deviation has definite significance; that is, represents, with a satisfactory degree of probability, a true association of the two variables.

The entire 358 counties included in the study had an average of 2600 hours of sunshine per annum. Among the individual counties the dental caries incidence rate was less than the mean for the entire group by 3.9 to 7.4 per cent, among the six classifications of children, for each 100 hours of additional sunshine, and correspondingly greater for lessoned sunshine hours. Winter temperature and latitude relationships are similarly interpreted in units of 10° F (from the mean winter temperature for the area of 25.5°) and one degree of latitude (from the mean latitude, 40.6 degrees).

The relation to sunshine is in accord with the results of controlled experiments on the addition of vitamin D to the diet and on exposure to ultraviolet light (artificial). Latitude, *per se,* determines the *air mass,* that is, the length of air column through which the sun's rays pass, with corresponding loss in ultraviolet intensity.

Mean winter temperature, independently of latitude, appears to be associated with caries incidence only among the younger and the older groups of girls. It is possible, as the authors suggest, that this is a reflection of the tendency of the boys and the 9–11 year girls to be out-of-doors regardless of temperature.

A direct effect of atmospheric pollution upon dental caries is indicated by comparison of these data with similar data for city children.* Direct correlations were noted, as previously, with hours

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* B. R. East, *Am. J. Diseases Children,* **61,** 494, 1941.

of sunshine, latitude, and winter temperature. Significantly, however, among 156 cities, in which mean values of these three variables were quite comparable with those in the rural counties, the incidence of dental caries was uniformly higher in each of the age–sex groups of city children. Moreover, there was a definite positive correlation between caries rates and size of city.

Various independent studies have indicated that air pollution over cities decreases in passing from the central area toward the suburbs. East holds that "it seems reasonable to assume that the larger the city the greater the area which has marked pollution of the air." Furthermore, both the latitude and the winter temperature relations are much more marked in the city data than they are in those from the rural counties.

ODORS. The offensive odors produced by oil refineries, grease rendering plants, and a multitude of chemical industries may be related to health in a specific and determinable manner, as in the case of throat irritation by sulphur dioxide, or the relation may be indefinite but none the less real; loss of appetite or of sleep, general malaise or even continuous mental resentment against an unnatural condition.

A study of industrial odors, especially those resulting from the refining of petroleum, was made some years ago at Providence, R. I. Inquiry among complainants showed nausea, headache, and throat irritation to be the most numerous causes of complaint, in the order mentioned. Physicians reported their belief that the odors were responsible for certain cases of illness that had come under their observation. They also believed that many conditions were aggravated by odors, notably pulmonary tuberculosis, asthma, and laryngitis.

Offensive odors may arise from other than industrial sources. Serious complaints of loss of sleep and of appetite were registered, and legal action threatened, by residents of a certain high-class residential area in Staten Island, N. Y., by reason of the proximity of a city dump with its ever-smoldering fires and accompanying smoke and odors of burning rubber, bone, and miscellaneous trash.

CARBON MONOXIDE. Automobile exhaust gases, and more particularly the exhaust from heavy trucks and buses, contain not only offensive products of imperfect combustion, but also measurable quantities of the extremely toxic carbon monoxide. This poses a serious problem in the ventilation of vehicular tunnels; even in the open air, the concentration of carbon monoxide may reach an undesirable level.

In some studies of Philadelphia traffic patrolmen, after an 8-hour exposure to the air of a busy traffic center, the concentration of carbon monoxide found in the blood was sufficient in many cases to be associated with mild subjective symptoms. Tests of the air of the streets in 14 cities at places and times of maximum traffic density showed an over-all average concentration of carbon monoxide of 0.8 part per 10,000, with maximum values of 1.7 and 2.9 parts. The latter value was obtained in a "tunnel-like" taxicab station. The values for the open street conditions do not represent a public health hazard except possibly for the traffic officers at certain congested centers.*

CANCER. Various investigators have employed statistical methods in search of a possible relation between smokiness and the incidence of cancer. In most instances the all-important factor of age distribution in the community has not been taken into account. Even when this correction is applied, it has been claimed that there is a definite relation between the use of coal, as compared with wood, and cancer death rates. Certain types of cancer are known to be associated with soot in industry and occupation (chimney sweeps), and some studies appear to show a correlation among cancer, smokes and fumes from industrial plants—oil refineries and smelters—and topography of the land.†

METEOROLOGICAL EFFECTS

FOG AND HAZE. It is frequently noted that the suspended atmospheric impurities, as measured by the air filter, and the humidity of the air are closely correlated. This may result, in part, from deficient air circulation on humid days, providing less dilution for a fixed amount of suspended impurity; but, in general, it is a more significant phenomenon. Suspended nuclei which, in the dry state, are too small to be filtered out, are enlarged by condensation of moisture and recorded on the filter. The tendency of moisture to condense upon suspended matter is demonstrated by the visibility data.

Aitken, of the British Committee, found that, at constant relative humidity in the air, it takes a fixed number of particles to obscure

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* E. D. Wilson, I. Gates, and W. T. Dawson, *J. Am. Med. Assoc.*, **86**, 319, 1926.

† Jerome Meyers, *Am. J. Pub. Health*, **20**, 581, 1930.

visibility. That is, the number of particles in a column of air to the limit of visibility is constant; visibility, in miles, is inversely as concentration of particles.

This relation is markedly affected, however, by atmospheric humidity. The number of particles, in a column of one square centimeter cross section, extending to the limit of visibility, under varying atmospheric conditions was found to be as shown in Table 29.

TABLE 29

Air Condition	Wet Bulb Depression, °F*	Number of Particles
Dry	7–10	220×10^8
Medium	4–7	171×10^8
Moist	2–4	125×10^8

* See p. 42.

This is the haze effect. It requires only about one half the number of particles to obscure the distant view in moist air that it does in dry air. In air of medium moisture a visibility of 1.71 kilometers (a little over one mile) is possible with 100,000 particles cubic centimeter; 10,000 particles would permit a visibility of over 10 miles.

Humphreys* shows that interference with solar radiation may be expressed by

$$I = I_o e^{-2n\pi r^2 x}$$

I_o being the incident and I the transmitted radiation; n the number of particles per cubic centimeter; r the particle radius; and x the distance in centimeters. This relation would indicate that Aitken was dealing with particles of uniform size distribution in each of his air condition classes and that the diameters of the particles were increased about one third in the moist, as compared with the dry condition.

Normally aqueous vapor does not condense upon small nuclei. The vapor pressure on the surface of a sphere being greater than on a plane surface, small droplets of water tend to evaporate into a "saturated" atmosphere. Only in a supersaturated air will condensation take place spontaneously upon a neutral particle. Much of the dust and smoke over cities, however, is hygroscopic; that is, it attracts water and will condense vapor at less than saturation

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* W. J. Humphreys, *Physics of the Air,* New York, 1929.

pressure. This property is often due to the presence of sulphurous or sulphuric acid upon the dust particles. These will condense moisture from a very dry atmosphere. It is to this hygroscopic property rather than to size that we must attribute the haze-making property of atmospheric pollution.

The effect of smoke upon fog is more definite. When moisture is beginning to condense from a supersaturated vapor, as when a saturated vapor is cooled, condensation takes place more readily if a nucleus of any sort is provided for the initiation of the process. The "smogs," smoky fogs, over cities are denser, blacker, and more frequent than in nearby areas. They diminish the normal hours of sunshine and the intensity of sunshine during the sunny hours. Overcast days, too, are darker. The recorded *hours of sunshine* fail to measure the total loss of useful light. Reference has been made to the loss of illumination and of ultraviolet light (p. 170).

INFLUENCE UPON TEMPERATURE. Suspended impurities also affect the heat rays. These are partially absorbed in the dust layer and do not reach the earth's surface. Reradiation (from earth to sky) at night is also retarded. This reduces the diurnal variation in temperature, by raising the minimum (night) temperature and lowering the maximum. Weather Bureau records frequently show a difference of 10 degrees between minima of city and near-by country, the city always being the higher. At Philadelphia, over a 10-year period, 1902–11, the following average data were obtained, comparison being with four adjacent control stations in the country:

	°F
Elevation of minimum temperature	4.4
Lowering of mean monthly range	4.9
Lowering of maximum temperature	0.4

Minimum temperatures were elevated by 11 to 14 degrees in the city on certain nights. A part of this effect is due to storage of heat in the masonry of a city, but further comparison of data leaves no question but that the major cause is city smoke.

ECONOMIC COSTS

PITTSBURGH. The early Pittsburgh studies included an estimate of the economic losses due to smoke. The figures are still impressive and were even more so when viewed against the economic and wage levels of 1913. They were based upon careful house to house surveys and inquiry and upon statistical data concerning laundry, dry-cleaning, and various other items.

The total annual cost to the city was estimated to be just under ten million dollars distributed among 16 items which may be grouped as follows:

	Million Dollars
Loss of fuel value through imperfect combustion	1.52
Laundry and dry cleaning	2.25
Household—painting, renewing wall paper, curtains, etc.	2.25
Stores—goods ruined, extra work	3.03
Public buildings, hotels	0.17
Extra lighting	0.73
Total	9.95

This amounted to an annual cost of about $20 per capita.

OTHER DATA. Various estimates of similar nature have been made for other places. A particularly careful study of conditions at Cleveland, Ohio, placed the annual per capita cost of atmospheric pollution in that city at $12 "and possibly twice that amount." Other city surveys have reported costs within this range. Less tangible items are depreciation of real estate values and the loss of profitable industry which might be induced to locate under more favorable atmospheric conditions.

The author has a letter from an official of the New York City Public Library seeking data on the content of hydrogen sulphide, sulphur dioxide, and sulphuric acid in the air of the city. He states, "We find that the paper in our books seems to be deteriorating very rapidly, not only on account of wear and tear, but also because of disintegration in the paper itself. We wonder if the condition of the air has anything to do with this matter."

The data for London (Table 19) may suggest an answer to this question. A deposit of 5 tons of sulphuric anhydride (SO_3) per square mile is equivalent to some 20 pounds of sulphuric acid over the area of the New York library.

PREVENTIVE MEASURES

SMOKE ABATEMENT

In theory, at least, smoke prevention is quite simple; it merely means complete combustion. This, in turn, requires an adequate air supply, properly mixed with the furnace gases, at a sufficiently high temperature, and maintained for a sufficient time before striking a cold surface.

Conditions for Complete Combustion. Various fuel coals require about 11 to 12 pounds of air per pound of coal for complete combustion. This includes an excess over the theoretical to allow for imperfect mixing and local variation. A well-adjusted draft gives a CO_2 content of about 15 per cent, as against 20 per cent for complete oxygen utilization. Too little air results in smoke, unconsumed volatile gases, and loss of heat. Excess air means a waste of heat carried off in the high-temperature flue gases.

Temperatures must be kept high for efficient combustion. Standard stoker designs call for a temperature of about 2500 degrees Fahrenheit. Combustion may be obtained at a temperature as low as 700 degrees, but it is incomplete and smoky. Moreover, time is required for the completion of the reactions of combustion. The hot gases must not be allowed to impinge too soon upon the cold surfaces of the boiler tubes. Witness the nearly complete combustion of a candle when burning free and the rapid deposit of soot upon any cold object held in its flame. A hard coal—anthracite—burns with a "short" flame. Its volatile gases are quickly consumed. Soft coking coals burn with "long" flames. Fireboxes must be designed accordingly.

Firing Methods. Obviously these conditions of smokeless combustion are best met in a modern type of mechanical stoker in which the feed of fuel is continuous and uniform, and the draft, carefully regulated and controlled by carbon dioxide measurements of the flue gases. The volatile hydrocarbons pass last over the hottest end of the firebox, and the whole operation is controlled by regulation of the temperature within the combustion chamber.

These exacting conditions are difficult or impossible to meet in intermittent hand firing with its periodic cooling of the whole mass and its variable air supply, always excessive at times of firing. This not only lowers the temperature, but also shortens the time allowed for combustion at this critical period. These natural shortcomings are aggravated by careless and unintelligent handling.

Codes and Enforcement. City sanitary codes generally prohibit the emission of *dense* smoke or limit it to a specified number of minutes and to a specified frequency per hour. The problem of the hotel and the apartment house is especially difficult to deal with.

With skill and good intentions, neither of which are conspicuous among the firemen of these establishments, the frequency and duration of periods of smoke emission and the intensity of the smoke itself may be reduced to a minimum but hardly ever to a negligible amount.

In New York City the inspectors of the Health Department endeavor to reduce the smoke from the smaller installations to a reasonable minimum by visits and instruction and, if this fails, by court action.

ESTIMATING SMOKE DENSITY. The difficult matter of defining the degree of density of smoke and of justifying the complaint, if it is brought into court, has been met by various devices. In Boston, Mass., the Board of Health prepared a scale of relative density by photographing a certain tall chimney in various stages of activity and reproducing a series of these pictures showing variation of smokiness from zero to most dense. The inspector merely compared a smoking chimney with this chart for his record of smoke density. This plan had the advantage of being readily interpreted by a city magistrate or a jury.

The *Ringleman Chart* is a more scientific standard. It consists of a series of squares ruled with black lines on a white background, the thickness of the lines being such that in each square there is a definite ratio of black to white. The chart is held at a sufficient distance from the eye to blur the lines into a uniform shade (compare acuity of vision, p. 133), and that shade is recorded which most nearly matches the shade of the smoke.

FLY ASH. Complete combustion of the fuel still leaves the problem of fly ash, the finely divided grey ash which rises through the stack. Fly ash is especially associated with forced draft and high stacks. Some of it floats for a long time in the air and contributes to haze and fog. It obscures natural daylight and is definitely opaque to ultraviolet light, although less so than is black smoke. If, as appears to be the fact, modern combustion methods result in a considerable increase in the amount of fly ash discharged into the atmosphere, the benefits of smoke abatement, from the public health point of view, are materially less than would be indicated by the reduction of visible smoke.

Fly ash may properly be regarded as one of the many industrial wastes classified as *dusts*. Remedial treatments are discussed in a later section.

OTHER CONTROL MEASURES

In addition to smoke, there are other types of undesirable atmospheric pollution for which control measures are required.

ODORS. For the most part objectionable odors are organic in nature. Such gases as sulphur dioxide (SO_2) and chlorine possesses odor but are undesirable on account of other properties. The offensive odors associated with the *rendering of fats and greases* are typical of a considerable class of organic odors.

In this instance a successful solution has been found in confining all gases from digesters and rooms in which offensive material is exposed, and exhausting these to the forced-draft system of the steam boiler. The organic odors are destroyed by high-temperature combustion.

A solution has been found in other cases through the use of *chlorine gas*. This is efficacious with organic compounds readily oxidized. For the best results a high degree of humidity must be maintained.

Ozone has been used with some success in certain situations, but its merits have been considerably overrated. It has been shown experimentally that it fails to react with such readily oxidizable substances as those contained in automobile exhaust gases under the conditions of high dilution of the ozone in the air of a garage. On the other hand, satisfactory reaction has been recorded with the organic odors accompanying the storage of sewage sludge. In this case the gases were confined and saturated with aqueous vapor, and a relatively high ozone concentration could be maintained.

Ozone affects the olfactory nerves and tends to limit or destroy the sense of smell for the time being. Many of the recorded beneficial effects are probably traceable to this fact.

ACID AND OTHER OBJECTIONABLE CHEMICAL FUMES. The difficulty experienced in classifying this group of gaseous wastes extends also to any discussion of their treatment. Scrubbing, a standard procedure for the recovery of water-soluble gases, involves the passage of the gases upward through a tower filled with coarse material, such as coke, against a countercurrent of water applied at the top.

Other possibilities for the recovery of volatile products, *having some commercial value,* suggest themselves to the chemical engineer as specific chemical problems. Unfortunately prevention of atmospheric pollution, for itself, is not likely to become a plant problem except under the pressure of damage suits or official condemnation. The great skill of the oil-refinery chemist, to mention only one example, is manifest to all who use his products, even without the lyric notes of magazine and radio advertisements. If some of this skill could be applied to the more prosaic work of odor prevention in the neighborhood of the refinery, there seems little doubt that an equally fine job would be turned in.

DUSTS. Suspended materials, stone dust, sawdust, and so on, are frequently removed from the immediate site of the shop operation by exhaust ventilation (see p. 112). Velocities of air flow are maintained through the exhaust system sufficient to keep the material in suspension. If now this air stream be passed through a chamber of such dimensions that the gases travel at greatly reduced velocity, much of the suspended material will be deposited. Such *stilling chambers* are always installed in connection with refuse incinerators, and their use is to be recommended wherever forced-draft combustion is employed.

A more efficient separation results from passage through a separator *cyclone,* Figure 29. The air stream enters tangentially and sets up a whirling movement which increases downward as in a vortex. The heavier material is thrown against the wall and slides toward the apex where it collects in a dustbox and is later removed.

The *bag filter* is more efficient for very fine and light material. Operating on the principle of the vacuum cleaner bag, its use is confined for the most part to recovery of valuable materials. In the manufacture of dried milk powder by the spray process, for example, much of the fine powder resulting from the evaporation of the spray remains suspended and is carried off with the moist air which must be continuously exhausted. This air is filtered through bags of fine texture for the recovery of most of the suspended dust.

Electrostatic precipitation is likewise capable of removing exceedingly fine material. It is employed in cleansing flue gases and will even remove smoke and fly ash. A central insulated wire runs vertically the length of the stack and is charged at a high potential —up to 70,000 volts—as against the grounded sidewalls. An intense electric field is set up; the particles are electrified with the polarity of the central wire and move in consequence toward the walls, where they collect in masses and drop to the bottom.

This process is employed to prevent the loss of such products as

Portland cement and zinc oxide during their manufacture. It appears to be too expensive for use in smoke or fly-ash separation.

THE TRUE COSTS OF PREVENTIVE MEASURES. The conclusion cited in the last sentence, that a suggested remedial treatment is too *expensive* to be *practicable,* is generally based upon a financial accounting in which benefits are balanced against costs; benefits, be it noted, in terms of values accruing to the offender, and costs, disregarding existing losses of natural benefits suffered by others. The Public Health Engineer is entitled to establish and employ a wider basis for the assessment of practicability.

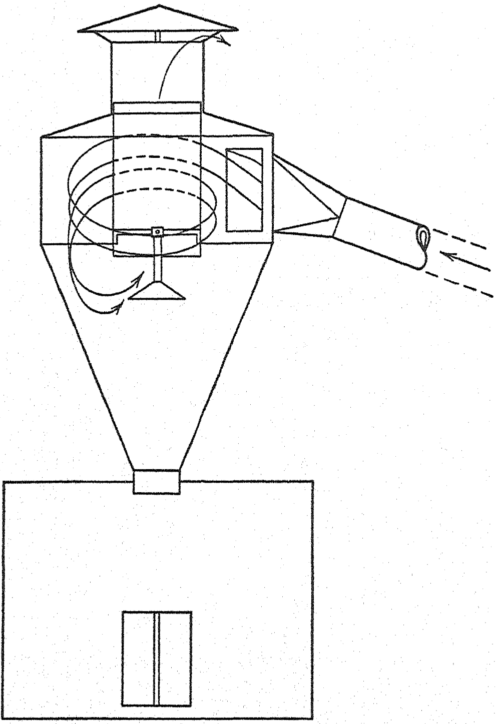

FIG. 29. Cyclone dust separator.

We hear much in current discussions of the *scale of living*. This refers to the extent to which a people can afford to enjoy those nicer and pleasanter things of life above the bare needs of living; the luxuries of a few years ago which are on their way to becoming the necessities of a few years hence. The availability of these things to the people at large has become the measure of a prosperous country and of prosperous times.

For the moment, we may lay aside all questions of the legality of practices which amount to a virtual confiscation of public rights in clean air and clean waters, with payment, at most, only in the general benefits which the community derives from its own industries. The basis of practicability, today, should be, can we afford to pay for the added costs of preventive measures?

In the matter of the pollution of streams by municipal sewage, cities are answering this question in the affirmative. Progress has been slow and has been greatly delayed by the difficulties experienced in dealing with the associated industrial waste problems. These are being solved and, it goes without saying, any additional costs are charged to production. Many other industrial problems, including those of gross atmospheric pollution, can be solved in a way that represents true economy if we put into the balance sheet the values recovered by the public; the luxuries, if we will, of clean air and clean water which we can afford to enjoy.

NOISE

Principle number 7 of the *Basic Principles of Healthful Housing** provides for: *Protection against excessive noises.* In justification of this provision the committee states:

> Excessive noise, a factor much neglected in the United States, is of serious moment in so far as it causes nerve strain and interferes with sleep and other physiological processes.

Noise may be regarded as an abnormal modification of the atmospheric environment and, as such, may conveniently be considered at this time.

THE NATURE OF NOISE

Sound is analogous to light in many ways. It is a physical phenomenon recognized subjectively as a physiological response by a special sense organ. Physically, sound is a series of alternate compression and expansion waves, traveling outward in all directions from the source, a vibrating body. In the unobstructed air it

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* *Loc. cit.,* footnote p. 26.

travels in straight lines, the wave front expanding as the surface of a sphere; hence it obeys the inverse square law.

Sound can be reflected by a plane surface (echo), projected as a beam (megaphone) or gathered and brought to a focus (parabolic microphone). Upon meeting a solid body sound waves are reflected, in part, but the successive pressure waves upon the face of the solid set up corresponding waves within which are transmitted through the solid. Sound *insulators,* such as Celotex, are porous nonhomogeneous substances which damp and scatter the waves and thus dissipate the sound instead of transmitting it. Sound waves are carried around a corner of an obstructing solid.

Sound waves of a uniform periodic nature produce a musical tone, the pitch of which is determined by the frequency of the vibrations. Thus pitch is analogous to color. In the perception of sound the human ear has a much wider range of frequency than has the eye for light. Visible light extends over a range of about one octave; audible sound, of something over nine octaves.

Noise may be defined as *disturbing sound.* Its disturbing features may reside in discordance, loudness, unexpectedness, or nonnecessity.

Discordance alone may not be disturbing. Witness the effect of the patter of rain on the roof or of the distant murmur of the surf; essentially nonmusical discordant sounds with a continuous and uniform average quality and intensity which makes them restful. Loudness aggravates discordance, but a neighbor's radio may be disturbing by reason of loudness alone, even when dispensing sweet music.

The sudden blast of a most musical auto horn may be disturbing because of its unexpectedness. It gives one a "start" and may be especially disturbing to one in the semiconscious state of dozing. Finally, there seems to be a purely mental disturbance caused by sounds that are unnecessary, like the continuous whistling of a small boy.

THE MEASUREMENT OF SOUND

Sound can be analyzed into its component tones and the relative intensity of each tone measured, corresponding to color analysis in light. It may also be measured in terms of its over-all intensity, corresponding to brightness. Like light for vision, its intensity is referred to a subjective physiological basis.

Sound has energy, as has an ocean wave, but its *auditory energy* can be expressed only in terms of *hearing*. There are inaudible waves, *supersonics,* corresponding to ultraviolet light; and certain central frequencies (like yellow light) are more audible, per unit of energy, than those toward the limits of the audible range. Thus, the measurement of the effect of sound upon the human ear is a somewhat complicated matter. It requires, in the first instance, a unit and a scale of reference and then an appropriate basis of comparison.

THE DECIBEL. As a unit of sound intensity, physicists have adopted the decibel. Strictly speaking the decibel is merely a ratio of intensities. An increase of 10 decibels means a *multiplication* of the intensity (energy) of the sound by ten. A further increase of 10 decibels again multiplies the intensity by 10 so that 20 decibels means a multiplication by 100.

Now, if we adopt as the starting value, the faintest sound that can be heard by the normal ear, then the decibel scale, referred to this sound as of zero decibels, becomes a scale of actual physical intensity of sound.

In Table 30 there is shown the decibel ratings of certain sound levels sufficiently defined to serve to orient this scale with experience. The corresponding intensities are also given, and from these the relation between decibels and intensity is obvious. It must be noted however that the intensities are physical measurements of energy. The ear hears decibels; that is 20 decibels is as much louder than 10 as 100 decibels is louder than 90. Obviously, we compare sound by percentage differences of intensity.

TABLE 30

MEASUREMENTS OF SOUND

Nature of Sound	Intensity	Decibels
Threshold intensity	1	0
Rustle of leaves in gentle breeze	10	10
Whisper—4 ft	100	20
Quiet suburban street; evening, no traffic	1000	30
Quiet automobile	100,000	50
Noisy city street	10^7	70
Pneumatic drill	10^9	90
Riveter—35 ft	10^{10}	100
Threshold of painful sound	10^{13}	130

(From *City Noise*)

Measurement by Comparison: the Audiometer. One procedure commonly employed for evaluating the audibility of sound or noise is by direct comparison with a sound of known intensity. It is a common experience that conversation in the midst of much noise, as in a subway train, must be carried on with sufficient loudness to overcome the background noise. This is the principle of the *audiometer*. A warbling note is reproduced on a phonograph and amplified through an attenuation system so calibrated that the intensity of the issuing sound can be adjusted to any desired sound level. The operator listens to this sound and modifies its intensity until it is just audible in the presence of the noise being measured. The *deafening effect* of noise, as it is called, is somewhat different against sounds of different pitch. For this reason test sounds of several different pitches are employed.

Direct Measurement: the Noise Meter. Sound waves possess energy which is the mechanical equivalent of their intensity. It has been seen, however, that not all sound is *heard* and that, within the audible range, a lesser proportion of the total energy is transformed into hearing near the limits than in the central band.

The noise meter is an apparatus which picks up the sound waves in a microphone and transforms their energy into electric impulses. The output at this point represents total energy. This is passed through a *weighting network* which analyzes the sound into frequency classes and modulates each class relative to its characteristic audibility. Thus the output, recorded as electric current, is closely proportional to the noise as it is registered by the human ear.

The noise meter also has a slight damping effect so that the indicating needle does not jump instantly in response to the momentary noise effect but rather integrates the effect of the past several seconds. This tends to give steadier and more significant readings.

RELATION TO HEALTH AND EFFICIENCY

In a comprehensive report of a commission appointed to study the noise problem in New York City, a considerable mass of medical opinion dealing with the relation of noise to health has been summarized. Briefly there appears to be satisfactory evidence for the following conclusions.

Hearing. The ear readily accommodates itself to variations in sound levels, but after frequent intense and recurring changes in level the muscles of accommodation become fatigued and fail to react. Under these circumstances hearing is seriously threatened. Occupational deafness is only too well known. It appears to be spreading to such outdoor occupations as that of taxi driver and traffic policeman.

THE HEART AND BLOOD PRESSURE. A sudden loud and unexpected noise, like the backfire of an automobile exhaust, excites the *fear reaction*. The heart action becomes irregular, pulse rate and blood pressure rise, and muscles tense for action. The extent of this reaction and its consequences are somewhat dependent upon personal sensitiveness. It is more pronounced among the nervous and the weak.

Controlled laboratory experiments, by Doctor Foster Kennedy, a neurologist and member of the commission, showed that the bursting of a blown-up paper bag increased the blood pressure in the brain of a subject to four times its normal value over a period of 7 seconds. This is more than the effect of hyperdermic injections of morphine or of nitroglycerine, the most powerful drugs available for this purpose. Kennedy believes that the effect of constant noise not only is emotional, but also leads to disturbance of the blood vessel apparatus and to an increase in the degenerative processes in the heart and arteries.

THE NERVOUS SYSTEM: SLEEP. Various eminent neurologists and psychiatrists have emphasized the grave effects of noise upon the nervous system. The effect is of the nature of a constant strain and drain upon nervous energy which tends to increase the incidence of functional mental and nervous disorders. This may lead eventually to nervous and mental exhaustion and neurasthenia. It is alleged that loss of sleep occurs, either as a cause or a symptom of mental breakdown, in about 75 per cent of the cases; that loss of sleep is one of the causes of insanity and that the production of sleep is one of the means by which insanity is prevented and also cured.

WORK OUTPUT. Noise interferes with attention and with concentration of thought. It is reported that Carlyle dreaded the sound of a cockcrow and that Schopenhauer, the German philosopher, was tortured by the crack of a carter's whip and exclaimed "noise is the true murderer of thought."

Professor J. J. B. Morgan found that, among pupils engaged in reading aloud, increased noise led to increased articulation, apparently in an attempt to keep the attention focussed. This, in turn, led to deeper breathing and to a decreased speed of reading.

Among office workers, tested experimentally by Doctor Donald A. Laird, a reduction in the noise level of a simulated city office by 50 per cent, resulted in:

> A saving of 19 per cent of the energy expended in typing, as measured by the working minus the resting metabolic rate.
>
> A general increase in the speed of typing. This was most noticeable with the fastest worker (7.4 per cent increase) and least so with decreasing normal speed. The slowest worker was unaffected by the noise.
>
> No change in the average accuracy. Slower workers made slightly fewer mistakes and rapid workers slightly more.

Factory workers, who in a very noisy room had been assembling 80 small units of equipment and making 68 mistakes, when moved to a quiet room, completed 110 units in the same time and made only 7 mistakes.

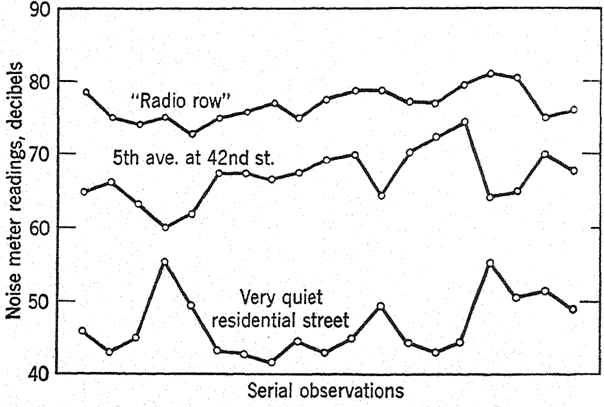

FIG. 30. Noise levels at three locations in New York City. Serial observations from minute to minute. (From *City Noise.*)

INTENSITY AND SOURCES OF CITY NOISES

The New York City Commission made a detailed survey of the noise levels in various city streets at all hours. Some of their data are reproduced in Figure 30. If it is recalled that ordinary conversation is carried on at between 60 and 70 decibels, these plotted points of instantaneous readings taken at frequent intervals over a short time on three characteristic streets may be readily interpreted.

RELATION TO TRAFFIC. Throughout 24-hour periods noise levels were closely correlated with traffic volume. The composition of the traffic, as among passenger automobiles, light trucks, and heavy trucks, is also reflected in the noise level. The horn was the chief offender, followed by poor brakes and general disrepair.

Overhead elevated trains contributed 3 decibels to the average and 7 decibels to the maximum noise of the street beneath. In other words, the intensity of the street noise was increased fivefold ($10^{0.7}$) by the passing of a train and the average intensity over the day was double ($10^{0.3}$) what it would be without the trains.

OTHER SOURCES. Other significant noise sources were outdoor radios, operated to attract customers in "radio row," whistles of steamboats, fire apparatus and traffic police, and building construction, especially steam shovel and riveter operations.

ANNOYANCE EFFECTS. A popular census of annoyance effects provides a measure of the relative frequency of occurrence of the nuisance, rather than of its specific annoyance potential. Thus, some 11,000 questionaires gave the distribution of sources of objectionable noises shown in Table 31.

TABLE 31

NOISE COMPLAINTS TABULATED BY SOURCES

Source	Per Cent
Traffic (including horns, cutouts, brakes, traffic whistles)	36.3
Transportation (elevated, surface cars, subway)	16.3
Radios (home and stores)	12.3
Collections and Deliveries. (Ashes, garbage, milk, etc.)	9.3
Construction (excavation, riveting)	7.4
Vocal (newsboys, peddlers, animals, parties)	7.3
All others	11.1

NOISE ABATEMENT

The experience of New York City, following the submission of the report of the Noise Abatement Commission, is suggestive of the possibilities, if not of abatement, at least of reduction of city noise.

PUBLICITY AND VOLUNTARY COOPERATION. Much was accomplished, temporarily at least, through voluntary cooperation. Considerable publicity was given to the findings of the Commission. Radiobroadcasting stations requested their listeners at 10:30 each night, to tone down their radios so as not to disturb their neighbors. Mail trucks were handled with less noise, following orders from the Postmaster. The major milk distributors fitted their delivery wagons with rubber tires and *their horses with rubber shoes*. This last was in the nature of a stunt, but the rubber tires remained standard equipment.

LAW ENFORCEMENT. Existing laws were being violated without attracting any attention from the police (a too common American habit). Enforcement of the regulations against the unnecessary use of the auto horn, especially by taxicabs, was ordered, and this one act made a most striking difference in the general noise level. Action was also taken against operators of ash and garbage collection trucks, street hawkers and others.

NEW LAWS AND CODE AMENDMENTS. Code amendments were adopted prohibiting the employment of commercial loud-speakers in store fronts without a police permit, and in any case, within 250 feet of a public school, court, or place of worhip when in session and within the same distance of a hospital.

The results were highly successful *for a time*. No noise meter was required by the average citizen to record the improvement. Visitors commented upon it, and we of the city realized the difference when traveling in other cities. But gradually interest waned; vigilance was relaxed; new noise sources replaced the old. It is highly probable that a noise survey undertaken today would show no lower noise levels than those disclosed in 1930.

The effort serves, however, to show what can be accomplished whenever the public becomes sufficiently aware of the true nuisance value of city noise to call for its control.

REFERENCE

City Noise, Noise Abatement Commission, Dept. of Health, New York City, 1930.

CHAPTER 8

INSECTS AND INSECT CONTROL

Disease Transmission and Disease Transmitting Insects

Insects and their allies* are the most important vectors of human-disease-causing organisms with the exception of man himself. Down through the ages malaria, typhus, plague, and yellow fever, all insect-borne, have killed vast numbers of human beings, caused tremendous economic losses, changed the course of military campaigns, and profoundly influenced the history of the world.

The medical importance of the arthropod group is due not only to the number of species of pathogens which they transmit, but also to the tremendous morbidity and mortality which these disease-causing organisms produce over immense areas of the world. In general the ways in which arthropods affect the health of man may be summarized as follows:

1. *By transmitting the agents of disease.* This may be accomplished in two ways:
    - *A. Mechanical transmission,* in which the arthropods may act as passive carriers of pathogenic agents. Example: a house fly carrying typhoid, cholera, or dysentery bacteria on its feet from a latrine to a kitchen.
    - *B. Biological transmission,* in which the arthropods may act as essential hosts of the pathogenic agents, in addition to transporting them. Two distinct types of biological transmission are known:
        - (*a*) Propagative, in which the pathogens undergo no cyclical changes, but merely multiply until they reach a sufficiently strong concentration to become infective to man. Example: plague bacteria in the flea, yellow fever virus in the mosquito, or spotted fever rickettsiae in the tick.
        - (*b*) Cyclical, in which the pathogens undergo cyclical changes and multiply within the arthropod host. The arthropod host is essential to the development and perpetuation of the disease-causing organism. Examples: *Plasmodium* parasites and filarial worms in the mosquito and trypanosomes in the tsetse fly.
2. *By invading the tissues of man.* Arthropods may burrow into the skin or enter the body through an opening. Examples: scabies mites in the skin, or myiasis due to fly maggots in the intestine or a body wound.

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* Invertebrate animals with jointed appendages at some stage of their life cycle; belonging to the Phylum Arthropoda.

3. *By inoculating poisonous substances.* Examples: the bite of the black widow spider or the sting of the giant scorpion.
4. *By being pests of man.* Arthropods may bite or cause excoriation of the skin with resultant discomfort and danger of secondary infection of the wound. Examples: bites of bedbugs or pest mosquitoes.

The important diseases transmitted by arthropods, including insects, may be classified according to the vectors with which they are associated as follows:

MOSQUITOES—Malaria, yellow fever, dengue, filariasis, equine and human encephalomyelitis.
NONBITING FLIES—Intestinal infections such as diarrheas, dysenteries, typhoid fever, and cholera. Also yaws.
BITING FLIES—Sand fly (Pappataci) fever, leishmaniasis, (kala-azar, espundia, and oriental sore), bartonellosis (oroya fever or verruga peruviana), tularemia, and African sleeping sickness (trypanosomiasis).
LICE—Rickettsial diseases (epidemic or classical typhus and trench fever) and relapsing fever.
FLEAS—Plague and rickettsial diseases (Murine or endemic typhus) and helminth diseases such as dog tapeworm.
TICKS—Rickettsial diseases (Rocky Mountain spotted fever, Sao Paulo typhus, fièvre boutonneuse, and South African tick fever), tularemia, relapsing fever, tick typhus, and certain forms of encephalitis.
MITES—Rickettsial diseases (Tsutsugamushi and related forms of scrub typhus and possibly others).
CONE-HEADED BUGS—Chagas disease.

ANOPHELINE MOSQUITOES AND MALARIA

Malaria is probably the most important of the insect-borne diseases, whether measured by geographical extent or by the damage which it causes. It is found in both the temperate and the tropical zones wherever the environmental conditions are such as to favor the development of the malarial parasite, *Plasmodium,* and the malarial mosquito, *Anopheles.*

THE PLASMODIUM SPECIES. The parasite is a minute protozoan requiring two hosts, man in which the asexual cycle takes place and the anopheline mosquito in which the sexual cycle is completed. Three species of malarial parasites are commonly recognized:

The Benign Tertian (*Plasmodium vivax*) with a cycle of 48 hours causing the fever to recur every third day.

The Malignant Tertian (*Plasmodium falciparum*) with a cycle of

24 to 48 hours which has a less regular recurrence of the fever, usually on the third day. This type is also known as Subtertian or Aestivo-Autumnal malaria.

The Quartan (*Plasmodium malariae*) with a cycle of 72 hours in which the fever recurs every fourth day.

Mixed infections of two, or even three, of these species have been known to occur.

LIFE CYCLE OF THE PLASMODIUM. In the asexual cycle in man the malarial parasites live within the red blood cells, multiplying by fission and thus entirely without fertilization. The cycle begins when the *sporozoites* are injected into the human blood stream with the saliva of the mosquito as it takes its blood meal. The *sporozoite* penetrates a red blood cell and there assumes an active amoeboid form known as a *trophozoite,* which grows at the expense of the red blood cell later forming a segmenting cell known as the *schizont.* At the end of 24 to 48 hours (*P. falciparum*), 48 hours (*P. vivax*), and 72 hours (*P. malariae*), the schizont becomes mature and divides into a number (6 to 36) of small cells or segments called *merozoites.* These rupture the walls of the red blood cells and emerge into the blood stream where they seek out other red blood cells and repeat the cycle.

After a number of generations of the asexual cycle have taken place in man, certain of the cells develop into the parent sexual cells, the *microgametocytes* (male), and the *macrogametocytes* (female). If these are taken up in sufficient numbers by the mosquito as it sucks up its blood meal, some of them remain undigested in the mosquito stomach. Here they undergo reduction and maturation divisions producing sexually mature male cells, *microgametes,* comparable to sperms, and female cells, *macrogametes,* comparable to ova. These conjugate in the mosquito stomach, uniting to form a motile *oökinete* which passes into the stomach wall and becomes surrounded by a characteristic thin membrane, the whole structure known as an *oöcyst.* In the *oöcyst* the malarial parasites multiply tremendously, eventually rupturing the oöcyst and liberating large numbers of minute motile *sporozoites* into the body cavity of the mosquito. Eventually the *sporozoites* find their way to the salivary glands where they are in position to be injected into a new victim thus completing the cycle.

The malarial parasite takes 8 to 15 days or more for its development in the mosquito, depending chiefly on temperature and humidity. In man a clinical case of malaria usually occurs 9 to 21 days or more after he has been bitten by an infected *Anopheles,* the time interval depending considerably on the species of parasite involved, number of parasites injected, and several other factors. It has been estimated that 150,000,000 parasites must be present in a human being before the clinical symptoms appear.

ANOPHELINE CHARACTERISTICS

Since the discovery in the last quarter of the 19th century and the first quarter of the 20th century of the part played by mosquitoes in the transmission of filariasis, malaria, yellow fever, and dengue, no group of insects have been more intensively studied. More detailed information concerning the classification, life histories, ecology, and control of mosquitoes (Family Culicidae) is available than for any group of insects of comparable size throughout the world.

APPEARANCE. Adult anophelines can be distinguished from most other mosquitoes in several ways. Most anophelines rest on a surface with the body held at an angle varying from 45° (*quadrimaculatus, albimanus,* and *culiciefacies*) to nearly 90° (*punctipennis* and *grabhamii*) with the abdomen and proboscis in nearly a straight line. Most culicines, on the other hand, hold the body more nearly parallel with the surface on which they are resting, with the head and proboscis bent downward at an angle to the abdomen. Anopheline mosquitoes, for the most part, have a rather definite pattern of wing spots, whereas culicine mosquitoes have wing scales of uniform color throughout, or, if the scales are of mixed colors, then there is no definite pattern (see Figure 31*).

Anopheles larvae lie parallel to the surface of the water and have no air tube, whereas the culicine larvae hang head down at an angle to the surface of the water, suspended by an air tube.

The anopheline pupae are often identified in the field by the expanded respiratory trumpets, whereas the culicine pupae have broadly conical or elongated respiratory trumpets. Boyd has summarized the chief differences by which the four stages of the anopheline mosquitoes may be distinguished as follows:†

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* Reproduced by permission of the Surgeon General, U. S. Pub. Health Service.

† M. F. Boyd, *Introduction to Malariology,* Harvard Univ. Press, 1930.

	Anophelini	Culicini (Broad sense)
Adults	Palpi of both male and female long; in former clubbed at tip, in latter about as long as proboscis. Posterior margin of scutellum evenly rounded. Wings of most species with definite color pattern, or "spotted wings."	Palpi of female much shorter than proboscis. Palpi of male long or short, but never clubbed at the tip. Scutellum posteriorly trilobed. Wings usually clear or without definite color pattern.
Egg	More or less boat-shaped with lateral floats, laid singly.	Elongated, ellipsoidal, or conical, without lateral floats, laid singly or in rafts.
Larva	Lying horizontally in the water just below the surface film, with which it is in contact at several points. Siphon absent.	Maintaining contact with the surface film only with the siphon, the body hanging downward. Siphon present, usually well developed and elongated.
Pupa	Siphons short and scoop-shaped, split down the front.	Siphons broadly conical or elongated tubular, unsplit.

It is estimated that at the present time there are approximately 2000 described species of mosquitoes, 200 species of anophelines, and about 20 important vectors of malaria throughout the world.

Standard reference works, some of which are listed at the end of this chapter, deal fully with species identification, a matter not to be lightly undertaken by the amateur.

DEVELOPMENT. Mosquitoes have four stages in their life cycle: the egg, larva, pupa, and adult (see Figure 31). The eggs hatch into larvae. There are four larval stages during which time the larva feeds and increases in size with each successive molt. After the fourth molting, the insect assumes the pupal form. In this stage no food is ingested, and a complete transformation occurs in both internal and external structure. When fully formed, the adult mosquito emerges from the pupa, rests a few minutes or hours, flies away to mate and feed, and a few days later begins to lay the eggs which will start a new generation.

The length of time required for a complete generation of mosquitoes depends primarly on temperature, and secondarily on such factors as type of food, *p*H of water, and availability of a suitable blood meal necessary for production of viable eggs in the fertilized female. In the northern parts of the Holarctic region only one gener-

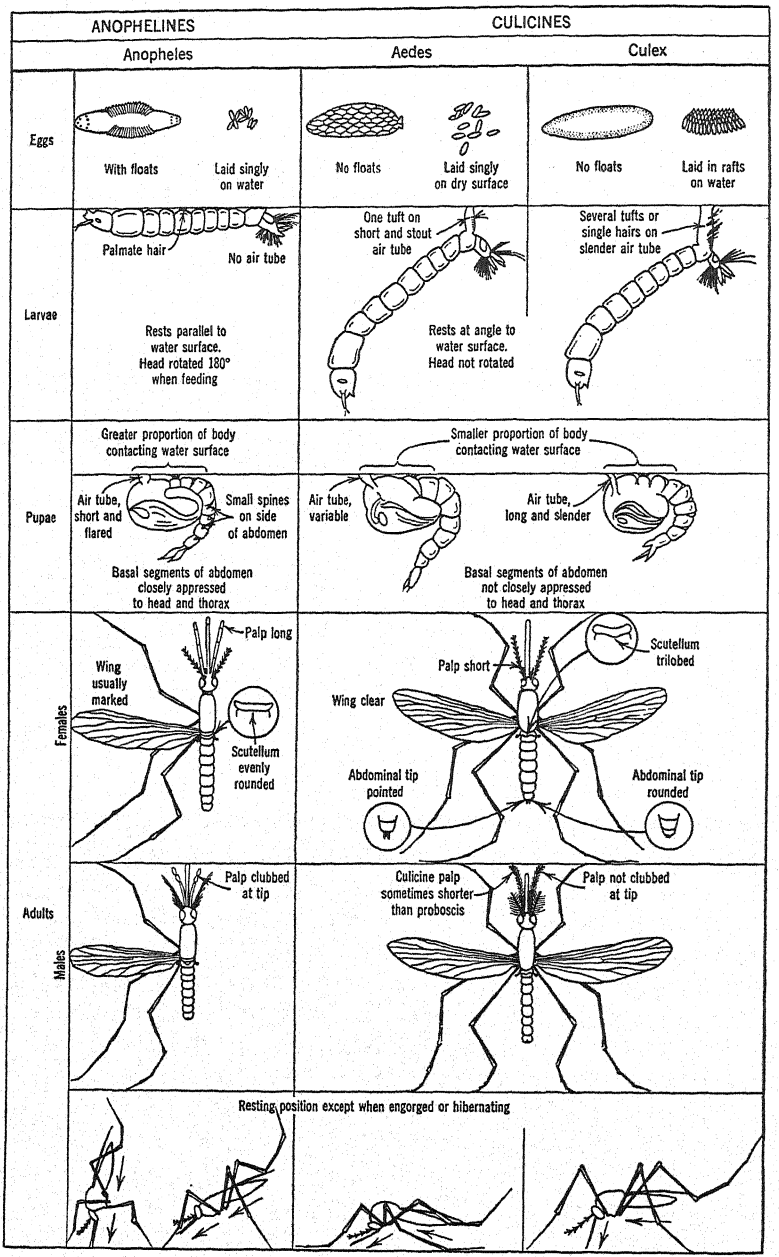

FIG. 31. Some distinguishing characteristics of the three mosquito genera,

ation may occur each year, the species passing the winter as fertilized females (members of the *A. maculipennis* complex) or as eggs (*A. walkeri*). In the temperate climates there are several generations during a breeding season, as many as six generations of *A. freeborni* occurring in California, and 8 to 12 of *A. quadrimaculatus* in southwestern Georgia. In the tropics breeding is continuous throughout the year. Some strong vigorous species such as *A. albimanus* may have as many as 20 to 25 generations a year under optimum conditions.

Water temperature is one of the most important factors in regulating length of the larval stages. In temperate United States the larval stages may take 3 weeks, particularly at the beginning and end of the breeding season; in the tropics the larval stages may be completed in as short a time as 5 or 6 days under optimum conditions.

FLIGHT RANGE. The flight range of most of the more important species throughout the world has been carefully studied. Adult mosquitoes are reared or collected, dusted with colored powders, or sprayed with aqueous solutions or aniline dyes, and released in test areas. In southeastern United States the female *A. quadrimaculatus* is generally believed to fly about a mile from its breeding place. In the Caribbean the female *A. albimanus* often flies 2 miles or more, whereas in the Sahara female specimens of *A. multicolor* have been found 8 miles from the nearest possible breeding place.

Male *Anopheles* are thought to fly in quantity only about half as far as the females of the same species. Thus, the presence of significant numbers of male *A. quadrimaculatus* in a station usually indicates breeding within half a mile, whereas the similar presence of male *A. albimanus* would suggest anopheline breeding within a mile of that particular light trap or stable.

The length of the flight range quite obviously is one of the most important factors in determining size of control zone. A control zone designed to protect an area from *A. quadrimaculatus* with a flight range of about a mile, is only one fourth as large as a similar one for *A. albimanus* with a flight range of 2 miles.

SPECIES SANITATION. Darling working in Panama noted that a given area usually has only one to three important vectors of malaria. He advocated that control measures be directed towards the important species only, thus proposing what has come to be known as *species sanitation.**

Since each species of mosquito has different preferences for breeding places, length of flight range, preferred host for blood meal, and susceptibility to infection with the malarial parasite, it is most important to know which anopheline vector is important in each control zone.

A knowledge of larval habitats is of utmost importance, since control measures by larviciding or by drainage are directed toward this stage of the mosquito. Determination of the species of anopheline larvae involved makes inspections more efficient and frequently results in large savings in money by indicating whole areas in which no larviciding is necessary. For example, in southeastern United States many streams are wholly neglected because the stream-breeding anopheline larvae have been found to be almost pure cultures of *A. punctipennis,* a rather poor vector of malaria. On the other hand, control measures are concentrated on ponds, reservoirs, lime sinks and other areas with quiet water, because the important vector, *A. quadrimaculatus* is known to prefer collections of impounded water.

Control measures must be adapted to the breeding habits of the larvae of the important vector species in the various parts of the world. Procedures which have been proved successful in controlling larvae of *A. albimanus* in sunlit ground water pools in Puerto Rico will not work in controlling *A. bellator* whose larvae breed in tiny collections of water between leaves of bromeliads high up in cacao shade trees in Trinidad, or for larvae of *A. stephensi* breeding in cisterns in India, or for larvae of *A. minimus flavirostris* in streams in the Philippines.

Many important vectors such as *A. quadrimaculatus* breed normally in fresh water; others, such as *A. albimanus,* breed in either fresh or brackish water. There is also a preference for alkaline or acid waters. *A. quadrimaculatus* and *A. punctipennis* prefer alkaline waters with a *p*H varying from 6.8 to 9.2, rarely as low as 5.1, whereas *A. crucians* larvae prefer more acid waters with *p*H range from 4.6 to 8.*

The idea of *species sanitation* likewise extends to control campaigns based on the destruction of adult mosquitoes. Spray campaigns using pyrethrum insecticides or DDT have been used successfully in areas where the principal vectors are domesticated, or semi-domesticated, as with *A. gambiae* in Africa or northeastern Brazil,

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* G. H. Bradley and W. V. King, *Pub. Am. Assoc. Advance. Sci. No.* 15, 1941.

culiciefacies in India, or *quadrimaculatus* in United States, but have not yet had much success with such "wild species" as *A. bellator* which feed on humans and later fly back to their breeding places.

QUANTITATIVE METHODS

The determination of the relative abundance of anophelines is an important part of malaria survey work and may be used also as a check on the effectiveness of larvicidal or drainage programs. Data may be gathered by dipping for larvae and pupae; catching adult mosquitoes biting; collecting adults in natural or artificial resting places, bait traps, light traps; or by a combination of these methods.

COLLECTION OF LARVAE AND PUPAE. Larvae and pupae are collected with white-enameled dippers. The number of larvae per dip is used as an index of the density of mosquito breeding and a guide to control measures. Larvae or pupae may be transferred by pipette from the dipper into the collecting bottle, preserved in 50–70% alcohol, or 4–5% formalin, and later determined in the laboratory. Where species are difficult to separate on larval structures alone, such as *A. freeborni* and *A. punctipennis,* it is necessary to collect the larvae and rear out the adults in order to determine what species are involved.

COLLECTION OF BITING MOSQUITOES. Biting mosquitoes may be collected on bare arms or legs with aspirators, or with chloroform or cyanide tubes. Such collections are frequently necessary to determine the species of mosquitoes present in the area. Sometimes biting records reveal that supposedly rare species are actually important carriers of malaria. Thus it was discovered that *Anopheles bellator* was an important vector of malaria in Trinidad by employing natives to collect whatever mosquitoes bit them. Among the mosquitoes thus collected 97 per cent were *bellator,* and 3 out of 725 of these "wild" *bellator* were found upon dissection to be infected with malarial parasites.*

COLLECTION FROM DAYTIME RESTING PLACES. During the daytime many species of *Anopheles* rest in cool dark quiet places such as barns, culverts, privies, hollow trees, or caves. Collections made from a number of such index stations are used in determining the anopheline hazard and the areas with greatest mosquito densities. A number of objections have been raised to this system. There is difficulty in

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* L. E. Rozeboom and R. L. Laird, *Am. J. Trop. Med.,* 22 (1): 83, 1942.

correlating collections made in index stations having large surface areas, such as barns or caves, with collections made in chicken coops or hollow trees. In some places, such as military camps, the available natural resting places are not sufficient to provide an adequate number of adult collecting stations. In order to overcome both these difficulties, standard-sized artificial resting places have been constructed. Some investigators use nail kegs or wooden boxes, whereas others prefer small privylike buildings.

COLLECTION FROM ANIMAL BAIT TRAPS. Not all species of *Anopheles* mosquitoes rest in barns or similar places during the daytime. Most of the South and Central American species of *Anopheles* in the subgenus *Nyssorhynchus,* for example, fly back to their breeding places in the daytime. For anophelines with such habits, animal bait traps have been employed. These are merely small roofed cages with horizontal slots in each side through which the mosquitoes may enter. An animal, such as a horse, donkey, or cow, is driven into the bait trap before sundown and left there until the following morning. The nocturnal-flying anophelines smell the animal, enter the trap through the entrance slots, feed on the animal, and are caught in the cagelike trap. In the morning inspectors drive out the animal and collect the mosquitoes. Collections from a series of such traps are used as an index of mosquito population in survey or actual control work.

COLLECTION FROM LIGHT TRAPS. Entomologists have used simple box-type trap lanterns for years to catch many types of night-flying insects. Members of the New Jersey Mosquito Extermination Association changed the design of the trap lantern so that it could be used to sample the night-flying mosquito population. Beneath the light bulb they placed a fan to suck insects attracted to the light downward into a screen funnel to the bottom of which was attached a killing jar. This type of trap is now used in many parts of the world to collect mosquitoes. Collections made in light traps have been used extensively by Army, Navy, and Public Health Service malaria-control personnel as a means of determining anopheline populations and thus checking on the efficiency of control operations or determining a potential malaria hazard. Light traps are effective only in collecting phototropic species or subspecies.

CONTROL PROCEDURES

The presence of malaria in any area in the world is possible only through a close biological interrelationship of three animals: the malarial parasite, the female anopheline mosquito, and human beings. Removal of any one of these partners will break the malarial cycle. Control efforts may therefore be grouped under three main headings:

1. Eliminating the parasite in man.
2. Protecting man from the bites of mosquitoes.
3. Destroying anopheline mosquitoes and their breeding places.

ELIMINATION OF THE PARASITE IN MAN

Control of malaria exclusively by mass prophylaxis with chemotherapy has not proved a satisfactory substitute for permanent mosquito control.

SUPPRESSIVE TREATMENT. Quinine and atabrine have a specific action on the gametocytes of *Plasmodium vivax* and *P. malariae,* and plasmoquine is especially effective on the gametocytes of *P. falciparum.* Quinine and atabrine have been used extensively to keep military personnel on duty in the field. In World War I the Allied troops used quinine. In World War II the Japanese conquest of the East Indies deprived the Allied Nations of this great source of quinine, and so Allied troops used atabrine. Reports on the use of quinine in Panama and of atabrine in the South Pacific leave little doubt that these drugs do have value in suppressing clinical attacks of malaria among military personnel stationed in malarious countries. None of these drugs, however, will wholly rid the individual of the parasite and hence he remains infectious.

Investigations of the value of suppressive measures in the South Pacific have shown that, although atabrine "would prevent clinical malaria when used in proper dosage, eventually there came a time when the drug had to be or was stopped. At this time the price of employing a suppressive drug instead of true preventives became evident. Benign tertian or *vivax* infections became clinically active following the termination of suppression which was ordered when combat activities were no longer essential. Another serious drawback in the use of the drug was that, in suppressing clinical malaria, it tended to give military commanders a sense of false security. This in turn in some cases led to neglect or delay in developing true preventive measures such as *Anopheles* elimination, screening, and individual protective measures against mosquito bites. However, the enormous benefits of the drug outweighed such considerations, and a policy of continuing all heavily infected troops on atabrine suppression while overseas has been adopted.*

It has also been noted that it is difficult to treat malaria patients who have had suppressive treatment. After the drug administration has been stopped, the parasites multiply rapidly and show a partial immunity to antimalarials. The number of recurrences is sometimes quite large as a result of the acquired tolerance to quinine or atabrine.

Mass Treatment. There is no unanimity as to the results of mass treatment programs, that is, the prophylactic treatment of the entire population of a community. During the years 1926–29 an intensive campaign of this sort was carried out in the Sardinian village of Torpe. The incidence of malaria actually increased each year during the experiment. On the other hand in the state of Georgia, U.S.A., a group treated with 0.1 gram of atabrine three times a week developed only 1.8 per cent of clinical cases of malaria as compared with 5.6 per cent in a group given 0.6 gram of quinine daily and with 31.7 per cent in an untreated group. Over a 2-year period the parasite index of the treated community was reduced from 17 to 0.3 per cent.†

PROTECTING MAN FROM THE BITE OF MOSQUITOES

Personal Measures. Personal protective measures such as the use of insect repellents and the wearing of head nets, light cotton gloves, tight leggings, and tough insect-proof clothing have, for many years, been standard textbook recommendations. During World War II Bushland and his associates of the U. S. Bureau of Entomology and Plant Quarantine, at the Orlando, Fla., Field Station, had developed a number of new repellents and made extensive laboratory and field tests of a number of previously known substances. As a result of these studies a number of preparations were made available to the Army and Navy which are effective against mosquitoes, sand flies, black flies, "no-see-ums" or "punkies"

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* J. J. Sapero and F. A. Butler, *J. Am. Med. Assoc.*, **127**, 503, 1945.

† R. A. Hill and M. H. Goodwin, Jr., *Am. J. Trop. Med.*, **18**, 339, 1938.

of the North Woods for two hours or more. These include Indalone, Rutgers 612, dimethylphthalate, and isopropylcinnamate. Prolonged use of some of these may give rise to a dermatitis. Care must also be taken to keep these repellents away from the eyes and mucous membranes, for some of them are very irritating.

Large-scale use of personal protective measures has been employed by both Army and Navy personnel in combat zones. The wearing of headnets, tight leggings, gloves, and insect-proof clothing has been emphasized especially for military police, shore patrols, and ground crews servicing airplanes at night whose work exposed them to the night-feeding *Anopheles* mosquitoes. When unit commanders have appreciated the importance of such measures and enforced them even though they interfered with the personal comfort of the men, there has usually been a lowering of the malaria rate in such units working between sunset and sunrise.

SPRAYING. Routine spraying of buildings will kill many adult mosquitoes. Quite obviously a spray campaign will be more successful with the domesticated or semidomesticated species such as *A. quadrimaculatus, A. gambiae,* or *A. culiciefacies* which remain inside houses either before or after feeding than with such "wild species" as *A. albimanus* or *bellator* which feed and later fly back to their breeding places. Serious outbreaks of malaria were prevented over a 5-year period in parts of Natal and Zululand by systematic spraying of native huts to kill *A. gambiae*. The dramatic conquest of malaria and the eradication of *A. gambiae* from northeastern Brazil were accomplished primarily by a larvicidal program and an intensive house-spraying campaign using pyrethrum insecticide, and in India the use of a pyrethrum spray apparently resulted in a great reduction in malaria transmission by killing engorged *A. culiciefacies* resting inside native houses during the daytime.

Pyrethrum sprays and aerosols are the most commonly used insecticides for the destruction of adult mosquitoes. Pyrethrum comes from the flowers of several species of *Chrysanthemum* grown principally in Jugoslavia, Uganda, and Japan. The active ingredients called pyrethrins are extracted from the dried flower heads with kerosene or other organic solvents. The spray materials are available commercially in two forms: a prepared ready-to-use spray, or a 20 to 1 concentrate (the extract of 20 pounds of pyrethrum flowers in a gallon of solvent and containing not less than 75 grams of total pyrethrins per gallon) which may be diluted with an odorless kerosene before using. Such sprays may be dispersed with the common household hand sprayer, pressure tank sprayers, or power-driven paint sprayers.

AEROSOLS. The basic idea of an aerosol is a fine mist which remains suspended for a long time in the air. Aerosols have been used for some years for the disinfection of the air of a room. For field use against mosquitoes the *aerosol bomb* or *Freon bomb* contains pyrethrum as the killing agent, sesame oil as the synergist, and the refrigerant Freon under high pressure as the dispersing agent.* Numbers of these bombs were manufactured and distributed during the war and supplied to Army and Navy personnel in many theaters. The spray is finer than the ordinary insecticidal spray and will disperse quite readily. It will kill mosquitoes, cockroaches, sand flies, house flies, and other types of insects. One pound is sufficient to treat 150,000 cubic feet of closed space.

RESIDUAL SPRAYING. Residual spraying with DDT is the most recent development in the war between man and the mosquito. DDT is the symbol for a complex organic compound (dichlorodiphenyl trichloroethane) which has the appearance of a white, lumpy powder. It is insoluble in water, but dissolves readily in such organic solvents as xylene, acetone, ethyl alcohol, kerosene, and Diesel oil. The outstanding quality of DDT as an insecticide is its long-lasting quality. When sprayed on the walls and ceilings as a xylene emulsion or a kerosene solution, the solvent evaporates, leaving a fine deposit of DDT crystals on the sprayed surface which will last for months. Mosquitoes, house flies, bedbugs, and other arthropods apparently absorb a toxic dose of the DDT through their feet as they walk over, or rest on, these sprayed surfaces even 3 to 6 months after the structure has been sprayed. About 10 to 30 minutes after lighting on a sprayed surface, mosquitoes begin to shake visibly, the *double delirium tremens,* and most of them are dead within an hour or two.

DDT is such a new insecticide that much remains to be learned regarding its toxicity to man, warm-blooded animals, fish, and other wild life. Laboratory studies indicate that it is not toxic to man or warm-blooded animals in the ordinary doses recommended for larviciding, aerosols, or residual sprays. Residual-spray crews, however, should exercise due caution to avoid dermatitis or more serious types of poisoning. Goggles and gas masks should be provided, and

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* L. D. Goodhue and W. N. Sullivan, U. S. Patent, 2,321,023, June 8, 1943.

an attempt should be made not to spill the spray on any part of the body to avoid absorption of DDT through the skin and mucous membranes.

MOSQUITO PROOFING. One of the first extensive demonstrations of mosquito proofing in the United States was made by the U. S. Public Health Service in Le Flore County, Miss.* A test area was set up in which all houses were screened, and a check area, with an equal number of houses, in which no screening was done. The difference in number of cases of malaria is shown in Table 32.

TABLE 32

		Screened Houses			Unscreened Houses		
Year of Observation	Year Screened	Number Houses	Number Occupants	Cases Malaria	Number Houses	Number Occupants	Cases Malaria
1926	1926	104	416	24	104	467	84
1928	1927	500	2057	206	500	2140	814

More recently successful demonstrations of the value of mosquito proofing have been made in Mississippi, Tennessee, and Alabama. In the latter state, in the Wheeler Dam area, where satisfactory mosquito control could not be obtained by other methods, mosquito proofing was found to be reasonably effective and economical. In 1939 there was no seasonal increase in malaria in the protected district, which had been thoroughly screened during the spring of 1938, whereas there was a noticeable rise from May through mid-September in the check area which was unscreened. The total cost was about $31 per house, much below the cost of larviciding in an area where effective drainage was impossible.

In malarious countries mosquito proofing should be used to supplement other types of mosquito and malaria control. In Central and South America during World War II, when routine mosquito-control measures failed to bring the number of *Anopheles* down to the level of satisfactory control, mosquito proofing of barracks and malaria discipline including use of bed nets often made the difference between a low malaria rate among military personnel and construction workers and a high malaria rate among nearby native villagers sleeping in unscreened houses without bed nets. Good screening has a further advantage in public health because it reduces the prevalence of fly-borne diseases such as typhoid fever, dysentery, diarrhea, and cholera.

Effective mosquito proofing requires that doors, windows and ventilators be screened with 16- or 18-mesh screen. Bronze or copper screening is more expensive, but lasts longer, than galvanized iron, especially near the ocean. Some of the new plastic screens will withstand corrosion due to salt sprays better than any type of metal screening and remain durable for 2 to 3 years.

Since every door offers a possible entrance for mosquitoes and increases the cost of maintenance, the number of doors should be kept to a minimum. In hyperendemic areas, a screened vestibule with outer and inner screened doors has been used to advantage in theaters, recreation halls, and restaurants. Doors should open outward, so that any mosquitoes on the screen will be forced away rather than carried into the building when the door is opened. Screen doors should be substantial with corners reinforced with metal or wooden triangles. The screen in the bottom panel should be protected with heavy ¼-inch hardware cloth. Some form of automatic closing device should be used.

Windows should be completely covered with screen, either by screening tacked over the entire opening, or by the use of movable screens. All cracks and knotholes, including cracks in the floor and spaces under the eaves, must be closed. Walls and ceilings may be covered with some tough durable water-resistant construction paper.

LARVICIDING

Larviciding is used extensively in malaria-control operations in situations where drainage or filling in low areas is not economically feasible. At many temporary projects, such as some Army camps, larviciding and personal protective measures are often the only form of malaria control which may be economically feasible. On permanent malaria-control projects larviciding should be used either as a supplement to, or during the development of, a drainage program. Whenever it can be demonstrated that the annual costs of area-wide larviciding are less than the annual maintenance and amortization costs of drainage for the same area, larviciding should be seriously considered. In general, in the northern parts of the *malaria zone,* where the breeding season is relatively short, larviciding is the preferred type of control. The farther one goes toward the tropics, with year-round breeding, the more important do the permanent types of control become. In the tropics drainage is fundamental to any permanent control program, almost invariably to be supplemented by larviciding to cover areas not completely drained or any new breeding places that may develop.

TYPES OF LARVICIDES. Larvicides fall into two great classes:

Contact insecticides, which kill through contact with the external and certain internal tissues of the insect.

Stomach poisons, which must be ingested to exert a toxic effect on the insect.

A knowledge of mosquito biology is essential in choosing the appropriate type of larvicide. Anopheline larvae feed at the surface of the water ingesting any particle on the surface small enough to be swallowed and may therefore be controlled by stomach poisons, such as Paris green, dusted on the water. Culicine larvae on the other hand feed below the surface of the water and are best controlled by contact insecticides, such as petroleum oils which kill by entering the breathing tubes.

The greatest single advantage of contact insecticides is that they kill all stages of both anopheline and culicine larvae and pupae by entering the respiratory systems. This quality makes petroleum oils the larvicide of choice in urban areas and military bases, and around institutions in the country where control of *all* types of mosquitoes is desirable. The action of contact insecticides is more prolonged than that of stomach poisons, since the film of oil will remain on the surface of the water for a week or 10 days. The presence of a film of oil on the water surface also tends to discourage oviposition, thus decreasing the amount of breeding possible.

Oils, however, have a number of disadvantages. They are messy and bulky to handle and transport; cannot be applied so far from the sprayer as can stomach poisons in powder form; frequently spread poorly over the surface of the water; and are very destructive to the rubber hose, gaskets, and diaphragms in sprayers. In general, the cost per acre of a single application of oil is several times that of dusting the same area with Paris green. In the tropics where, during the rainy season, it may rain during part of every day, the long-lasting oils may be preferable, in some breeding places, to Paris green, which may be washed away or sink before the larvae have had a chance to ingest it.

Stomach poisons, such as Paris green, are used wherever the program is designed chiefly for malarial mosquito control, such as the Malaria Control in War Areas Program of the U. S. Public Health Service during World War II. Paris green may be applied in areas where it is not economical or practical to use other larvicides. If advantage is taken of favorable wind currents, the dust can be carried long distances from the dusting machine to places inaccessible to oiling crews, penetrating dense growths of emergent vegetation, such as water hyacinths or mangrove trees, which block oil-spray streams or film spread. It is easy to transport and is far cheaper than oil, both as to cost of materials and labor.

The disadvantages of Paris green as a larvicide are that it kills anopheline, but not culicine larvae; that it kills adequately only second-, third-, and fourth-stage larvae (since the first-stage larvae are so small that they frequently do not ingest particles of the Paris green dust, and the pupae do not feed at all); that it is difficult to apply uniformly on windy days; and that it is easily washed away, or sunk, by hard rains.

LARVICIDAL OILS. Many kinds of petroleum products have been used in malaria-control operations, such as crude oil, fuel oils ranging from light distillates like kerosene to heavy black oil, and mixtures of oil products and other chemicals such as kerosene and pyrethrum extracts.

The lighter, more volatile distillates, such as gasoline and kerosene, penetrate the larval and pupal breathing tubes more rapidly and are more toxic than the heavier fuel and lubricating oils which form more stable and permanent film and kill primarily by suffocation. A good mosquito oil should have the following characteristics:

Enough of the low-boiling petroleum fraction to insure rapid penetration of the mosquito respiratory system.

Enough of the high-boiling petroleum fraction to provide a stable long-lasting film on the water surface.

High toxicity to larvae and pupae.

Ability to penetrate rapidly through flotage and vegetation.

Low cost.

In general, No. 2 fuel or Diesel oil meets these requirements, is easily obtainable in most parts of the world, is fairly uniform in quality, and may be used in either hand- or power-spraying equipment.

When Diesel oil is not available, waste crankcase oil diluted with three times its volume of kerosene may be usefully substituted. The crankcase oil is not a uniform product and is usually full of dirt and pieces of metal. It should be settled in a tank and the sediment rejected. Even then spraying crews may spend more time cleaning spray nozzles than the equivalent of the cost of standard Diesel oil.

Since 1943, DDT larvicides have been tested extensively and have proved so successful that they have practically replaced other larvicidal materials. In general, the spray solutions contain 0.05 to 0.1 pound of DDT dissolved in 1 gallon of kerosene or Diesel or fuel oil No. 2 with one half of one per cent of a spreading agent (such as B-1956 made by Rohm and Haas Company, Philadelphia). Such DDT solutions sprayed from conventional hand or power sprayers at a rate of application of one gallon per acre give as good control of mosquito larvae as, or better than, 1 to 3 pounds of Paris green diluted with 5 to 30 pounds of hydrated lime, or 20 to 40 gallons of fuel oil, applied to areas of equal size. Even better control may be obtained using a mist sprayer. These sprayers are provided with special nozzles which mechanically atomize the DDT oil solution, allowing the mist to be carried by the wind over the area to be treated. Either method results in enormous savings in materials, equipment, and labor, compared with the ordinary larvicidal techniques using Paris green or petroleum oil alone.

METHODS OF APPLICATION. For species such as *A. subpictus* and *A. stephensi* and the culicines, *Aedes aegypti* and *Culex quinquefasciatus*, which breed in cisterns, wells, and small confined bodies of water, it is sufficient merely to pour a little oil on the breeding places. The *drip can,* as developed and used in Panama, is an adaptation of this idea. It was simply a tin can with a hole punched in the bottom and set above the stream, ditch, or pool to be oiled by the slow continuous dripping. In the first experiments a piece of string or cotton waste was wound around a nail just below its head and pushed through the hole in the drip can from the inside. Then the quantity of oil allowed to drip through the hole could be regulated by pushing the nail up or down. Later, lock spigots, which could be adjusted by a key, were soldered to the drip cans and gave more uniform and satisfactory results. Drip cans are not entirely satisfactory. In streams or ditches with any perceptible flow the oil tends to follow the current down the center rather than to spread to the edges where the larvae are breeding, so that much oil is wasted, and many larvae are not killed.

Bag oilers can be used either in streams or in standing water of a small area, such as the end of a main or lateral drainage canal. The bag is filled with sawdust, rags, or cotton waste soaked in oil. A bag may be anchored so that it floats at the surface or may be submerged. Oil will rise to the surface from such a bag for a week or more after it has been anchored in place. If DDT is dissolved in the oil, the residual effect will oftentimes last much longer.

Hand sprayers are usually of the *knapsack*-type 2- to 5-gallon cans carried on the back. They may be fitted with a piston pump, a diaphragm pump, or a pump in the handle just behind the nozzle, the so-called trombone type. The piston-pump type is preferred. The compressed air sprayer generally has a cylindrical can to which is welded a piston-type air pump. About 50 to 100 strokes of the pump handle will create a pressure of 50 pounds inside the sprayer which will last from 3 to 10 minutes. With either type, a man can distribute about 30 to 40 gallons of oil per day under average conditions.

Power sprayers of various types are also used. The *barrel pump* was one of the first types used in mosquito control in Panama. Later, pumps were designed to be driven by gasoline, Diesel, or electric motors. The smaller types operate at about 10 pounds pressure. Orchard-type sprayers capable of mixing oil and water under pressure of 400 to 500 pounds per square inch have been mounted on trucks or boats. The tank of such a pump is filled with three parts of water to each part of oil and mixed under pressure to form an oil-water emulsion which may last for 2 to 4 weeks when sprayed on watered areas, as compared with a week to 10 days for ordinary Diesel oil.

RATE OF APPLICATION. In order to obtain adequate control, it is necessary to apply from 5 to 50 gallons of oil per acre, depending on method of application; vegetation, flotage, or debris on the water surface; and operational technique. Reservoirs with small amounts of vegetation require less oil than open swampland, whereas bunch grass pasture lands and edges of impounded water with much nonvital flotage require the heaviest applications. In general, 25 to 40 gallons of oil per acre will give adequate protection. The addition of 1 to 2 per cent of black oil to the Diesel oil will enable the oil gangs to see which areas have been treated, and prevent the necessity of respraying watered surfaces. The addition of 1 or 2 per cent of cresylic acid, castor oil, or phenol will greatly increase the spreading power of larvicidal oils.

Neither gasoline nor any other petroleum oil should be used on potable waters stored in metal containers, because small amounts of oil are absorbed on the sides and give an unpleasant taste to all water subsequently stored. Petroleum oils may be applied to natural reservoirs used for storing drinking water, however.

STOMACH POISONS

Paris green is the only stomach poison commonly used as a larvicide in mosquito control. It is a double salt of copper meta-arsenite and copper acetate. According to the United States Federal Insecticide Act of 1910, Paris green must contain at least 50 per cent arsenious oxide and not more than 2.5 per cent water-soluble arsenious oxide. At least 95 per cent should pass a 325-mesh screen in a machine or hand-shaking test. The toxicity of various commercial brands of Paris green may be tested in the laboratory by pan test, using the same Paris-green-diluent mixture and rate of application as in the field. At the end of 2 hours all second-, third-, and fourth-stage and many first-stage larvae should be dead.

In practice, Paris green is always diluted with an inert powder such as soapstone, hydrated lime, calcium carbonate, wood ashes, or merely road dust. The proportions of diluent vary according to the method of dusting to be employed and the nature of the terrain.

Spot dusting or *hand casting* is the simplest technique and may be employed to cover a range of 15 or 20 feet in the clear. For this use the mixture need contain only 1 or 2 per cent of Paris green. *Hand dust guns* may be employed with 2 to 4 per cent mixtures in narrow streams and ditches and for larger areas such as extensive flat swamplands, with mixtures of 4 to 10 per cent Paris green. Trained men dusting with wind to their backs may get effective kill in such situations in strips 25 to 200 feet wide. For ponds, lime sinks, and broad flat marshes or pasturelands a *power duster* is more economical. It will use mixtures of 10 to 15 per cent Paris green and give good control in strips of 50 to 500 feet in width, depending on the amount of vegetation covering the water, wind conditions, and operational techniques. Airplane dusting with 25 to 50 per cent mixtures have been used, especially in broad-acreage swamps with abundant vegetation where the water is too shallow for boats and the area is inaccessible for hand or machine labor. In such situations airplane dusting is often the cheapest form of control.

Rate of Application. Theoretically, ½ pound of Paris green per acre will give satisfactory control of anopheline larvae if it can be dispersed as a fine cloud over the water surface. In actual practice somewhat higher rates of application are sometimes necessary in order to obtain effective kill. In areas with dense vegetation and prolific breeding, 1 to 4 pounds of Paris green per acre with 15 to 40 pounds of inert carrier may be necessary to secure control. When Paris green is applied at standard larvicidal rates, it is not poisonous to fish, livestock, or human beings, but care should be taken not to overdust an area, or to "dump" Paris green. A body of water is usually well dusted if a dust cloud of moderate density can be observed drifting over the area. If the water has a noticeable amount of fine green powder, almost invariably it has been overdusted.

NATURALISTIC METHODS OF CONTROL

Alteration of Salinity. Permanent elimination of anopheline larvae from low-lying marshes along the seacoast has been accomplished by increasing or decreasing the salinity.

Increasing salinity or *salting up* as a means of eliminating anopheline breeding is well illustrated in the classical example of Durazzo, Albania. By installing tide gates (see p. 229) in reverse position a brackish marsh was transformed into a sea-water lagoon, making conditions unfavorable for the breeding of *A. elutus,* the dangerous vector along the coastal parts of the Balkan peninsula. "Within two years, breeding over an area of fifteen square kilometers was reduced to zero, while the profits to the Government of an existing fish concession more than equalled the cost of the operations." *

In Falmouth, Jamaica, BWI, mangrove swamps along the sea were cut off from the sea by sand bars. After the first heavy rains, the sea water was diluted sufficiently to permit prolific breeding of *A. albimanus.* In a population of 8000 people, 4400 cases of malaria developed with 138 deaths, and the spleen rate rose from 5 to 90 per cent. When sea water was readmitted and the salinity increased, *albimanus* breeding decreased, and the malaria outbreak subsided.†

On Vieques Island, Puerto Rico, the largest single breeding area for *A. albimanus* was a 400-acre mangrove swamp. Two openings,

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* L. W. Hackett, *Malaria in Europe,* Oxford Press, London, 1937.

† B. E. Washburn, *Am. J. Hyg.,* 17, 656, 1933.

one 55 feet and the other about 30 feet wide, were constructed into this swamp from the sea. The salinity of the lagoon was increased to as much as 90 per cent sea water in less than 3 weeks. The average tidal range was 0.8 foot. As the salinity in the lagoon increased there was a noticeable decrease in anopheline breeding, which was later reflected in reduced size of adult anopheline collections in nearby animal bait traps. Breeding was greatly reduced in water of a salinity of 50 per cent and almost entirely eliminated when the salinity reached 75 per cent sea water. The action of sea water with respect to *albimanus* breeding appears to be twofold. It reduces the number of females laying eggs in the brackish water, and it reduces or prevents embryonic development and hatching of the eggs.*

Decreasing salinity has also been found to be advantageous in certain situations. During the reclamation of land in the Zuyder Zee, North Holland, it was found that, as the salt leached out of the soil, *A. maculipennis* variety *atroparvus,* the local malarial vector which breeds in brackish water, was replaced by the variety *messeae,* a noncarrier which prefers fresh water. Excluding salt water from marshes in Malaya was likewise found useful in controlling both *A. sundaicus* and *A. barbirostris.*

In projects aimed at the elimination of anopheline breeding from coastal waters through control of the salinity of the waters, the construction of permanent all-weather openings to the sea is of primary importance. This generally requires detailed engineering studies of the hydraulic and tidal effects, and expensive construction equipment and methods.

ALTERATION OF SHADE. In general, the tropical anopheline mosquitoes can be divided into two groups: those that prefer sunlight for breeding, and those that require shade. By and large, the sun-loving species are the more dangerous carriers of malaria. Lumbering operations in southeastern United States have transformed many a forest with a well-shaded forest floor into an ideal breeding place for *A. quadrimaculatus,* a broken-shade lover. In the Federated Malay States intensive jungle clearing practically eliminated the relatively unimportant shade-loving species, *A. umbrosus,* and made suitable breeding places for the sun-loving and important vector species, *A. maculatus.* In Trinidad clearing of virgin forest or cacao plantations made conditions favorable for the sun-loving *A. aquasalis* and decreased the numbers of the less unimportant *A. apicimacula.* The

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* H. S. Hurlbut, *J. Parasitol.,* 29, 356, 1943.

same phenomenon has been observed in Argentina where forest clearing has been mentioned as a cause of explosive outbreaks of malaria by creating ideal breeding places for *A. albitarsis, A. "tarsimaculatus,"* and *A. argyritarsis.*

In Assam quick-growing shrubs such as *Duranta, Lantana, Hibiscus,* and *Tarapat* have been planted along the banks of narrow streams to control breeding of *A. minimus.* The dense shade apparently had little effect either in inhibiting ovipositing females or in its action on the larvae, but it did kill the grass in the streams, thus reducing the protection available for larvae and increasing water movement. In this case, dense shade is defined as that under which grass will not grow.

In Ceylon breeding of *A. culiciefacies* in field channels was controlled by planting rice, and in Cuba thickets of *Ficus benjamina* have been planted to shade out *A. albimanus.* The shade appeared to cut down the growth of algae and other vegetation and thus to deprive the larvae of both food and protection from fishes.

ALTERATION OF FLORA. In many ponds in the United States and the Caribbean region there is a natural reduction in amount of anopheline breeding as the water surface becomes progressively more covered with such water plants as the duckweeds (*Lemna, Spirodela,* or *Wolffia*), with the aquatic ferns (*Azolla* and *Salvinia*), or plants such as the water hyacinth (*Piaropus*) or water lettuce (*Pistia*). In places it has been noted that there is relatively little breeding of malarial mosquitoes in ponds or ditches with water lilies (*Nymphaea*) or water shield (*Brasenia*) which have broad leaves nearly covering the water, thereby excluding the larvae by mechanical action. However, naturalistic control by such methods has a very limited application and is of minor value.

POLLUTION. Most anopheline larvae prefer relatively clean water, whereas a number of pest mosquitoes such as *Aedes vexans* and *Culex quinquefasciatus* thrive in polluted water. Large numbers of anopheline larvae are seldom found in waters heavily polluted with domestic sewage, bagasse from sugar mills, or wash water from laundries. Deliberate pollution of small collections of water has been attempted, using chopped grass, herbage, or leaves. This method has its limitations in practical control, but, as one authority has written, "Malariologists should be alert for opportunities to cheapen control by using industrial, agricultural, or home waste to pollute breeding places. Pig-raising may improve the economic status of a community, while, with a little direction, it tends to free pools or ponds of malarial vectors."*

DESTRUCTION OF WATER-HOLDING PLANTS. *A. bellator,* one of the most dangerous malaria vectors in Trinidad, BWI, breeds almost exclusively in collections of water between the leaves of bromeliads, pineapple-like plants growing on the branches and trunks of jungle trees or *immortelle* trees used to shade cacao plantations. During 1941–43, U. S. Army and Navy malaria-control officers on Lend-Lease bases in Trinidad hired men to climb these trees and cut off the bromeliads with machetes. This type of control was expensive, amounting to as much as $1.50 a tree, and $40 to $50 per acre. Later high-pressure sprayers, used by forest entomologists in Massachusetts to spray tall forest trees infected with Gypsy moth larvae, were brought to Trinidad. It thus became possible to spray solutions of copper sulphate 50 to 100 feet up into the jungle trees. The minute quantities of this chemical which dropped into the bromeliads killed them just as effectively as copper sulphate kills microscopic plankton growths in water reservoirs.

INTRODUCTION OF NATURAL ENEMIES. The use of viruses; bacteria; protozoa; fungi; predacious insects such as water beetles and dragonfly naiads; fish; amphibians; reptiles; bats; birds; and insectivorous plants have all been recommended at various times in the biological control of mosquitoes. Of all the natural enemies of mosquitoes, only certain surface-feeding fishes have been shown to have any practical value in malaria control. The top minnows (*Gambusia, Lebistes, Panchax*) in fresh water, and the killifishes (*Fundulus*) in salt water have proved to be the most useful.

Lebistes reticulatus ("guppies" or "Barbados millions") has been introduced into various West Indian islands and parts of northern South America, especially for controlling yellow fever mosquito larvae in cisterns and other artificial collections of water.

Gambusia affinis is the most important fish species employed in malaria control. They multiply rapidly, giving birth to successive broods of living young throughout the warm season in temperate climates, and throughout the year in the tropics. They feed chiefly at the surface; show a marked preference for mosquito larvae; are easily transported; and are adaptable to clean or polluted, fresh or brackish, natural or confined waters. *Gambusia* will give good control in most small containers, provided that there is not too much

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* P. F. Russell in *Am. Assoc. Advance. Sci. Monograph* 15.

vegetation, algae, or flotage to protect the mosquito larvae. They are especially suitable for the control of species which breed in wells and cisterns, such as *A. stephensi* or *culiciefacies* in India, or *A. quadrimaculatus* which sometimes breeds in numbers in garden lily ponds in the United States.

MANAGEMENT OF WATER FOR MALARIAL CONTROL

It was the studied opinion of the late Dr. Henry Rose Carter that at least 50 per cent of all malaria was *man-made*; that it resulted as a by-product of engineering activities of various sorts in which too little attention was given to mosquito-breeding possibilities. Doctor Carter used to define a *borrow pit* as a pit from which construction engineers borrowed fill with no intention of returning it. These pits, so frequently left alongside highway and railway construction, and the crossing and cutting off of natural drainage lines by road embankments without provision of suitable culverts for drainage, he held to be responsible for an enormous amount of unnecessary mosquito breeding.

The remedy for these situations is obvious. There are some other types of engineering development, however, in which enhanced mosquito breeding is due, not so much to carelessness and disregard of the possibilities, as to inherent conditions. Some of these require more detailed discussion.

IRRIGATION. In Arkansas, Louisiana, and Texas *A. quadrimaculatus* often breeds in enormous numbers in rice fields, and the same is true in Java of *A. aconitus*. *A. albimanus* breeds in irrigated sugar cane fields in the Caribbean Islands. In southwestern United States, the important vector *A. freeborni* is found more frequently in small collections of seepage water from defective irrigation systems than in the irrigated fields themselves.

In most malarious regions of the world there are laws regarding the maintenance of irrigation systems and the regulation of flow in such systems, providing either for drainage after the crops have been gathered, to prevent breeding in stagnant pools on the fallow land, or for a regular alternation of flooding and draining at time intervals short enough to destroy larvae and pupae before a brood of mosquitoes can emerge. A program based on a 9-day period of flooding and a 2-day period with the water drained off has worked successfully in many parts of the world.

River Training. In hilly country where stream-breeding anophelines are the principle vectors of malaria, it is often possible to obtain control by confining the water to a relatively narrow clean channel with a swift current, which offers a minimum number of breeding places. In the hilly sections of Puerto Rico and Vieques, stream channeling has been so successful in the elimination of *A. albimanus* that larviciding has actually been omitted for periods of several months.

Flushing. Similar situations are dealt with at times by installing a system for periodic flushing of the stream bed, much as sewers on flat grades are flushed. Water is impounded in the upper reaches of the stream and is let down as desired in a sudden flush which, after the manner of a cloudburst, cleans out the stream. The flushing system may be made automatic, with a siphon, or it may be manually controlled. Flushing was employed in Panama in 1916 to control *A. albimanus,* and it has been recommended in certain places in the Orient for the control of *A. maculatus* and *A. minimus.*

Regulation of Water in Impounding Reservoirs. During the last half century many large dams have been built in southeastern United States for hydroelectric power, flood control, and navigational purposes. In the large bodies of impounded water thus created, *A. quadrimaculatus* finds ideal breeding conditions, especially constant water level, aquatic and semiaquatic vegetation offering protection to larvae, large collections of fine flotage and debris along the shore line, minimum wave action, and absence of natural enemies.

Studies of the U. S. Public Health Service and the various state health departments, and, more recently, of the Tennessee Valley Authority, have resulted in legislation and practices which aim to control malarial mosquito breeding through naturalistic or biological methods. These are all directed toward the development and maintenance of a clean water surface through proper reservoir preparation, water level fluctuation, and shore line maintenance.

DRAINAGE

The value of drainage in reducing malaria has been known for centuries; as have also many of the basic engineering principles of drainage design and construction. Refinement of general drainage practices for malaria control purposes, however, could not take place until certainty of mosquito transmission of the disease had been established, and beyond that until species vectors and their habits became adequately known. Perhaps the earliest application of those specialized biological engineering practices which we term "malaria control drainage" were by Gorgas and Le Prince in Havana from 1901 to 1903, and by Sir Malcolm Watson in Malaya in 1902. Also in 1904 Gorgas, Le Prince, and others started intensive malaria mosquito control in Panama, using all known methods but chiefly drainage. The Panama campaign was so successful that the British sent over a special commission to study that epoch-making work and later copied many of its procedures in various parts of their far-flung empire. Much work in the aggregate was done also during the past 30 years by the Dutch in Java, and by the Rockefeller Foundation in widespread small-scale demonstrations throughout the world.

In the United States selective drainage for malaria control was first practiced extensively during World War I by military agencies around military bases in malarious areas. This was followed in the '20's in some of the more malarious Southern States by limited programs of antimalarial drainage, promoted and designed by state and local health department engineers and financed by local governments and private individuals. State and local convict forces were also used. The most significant benefits from this work were realized in and around urban areas, rather than rural, although communities with as little as 500 people participated. Marked expansion occurred from 1931 to 1940 as a result of work relief programs; with as many as 30,000 workers employed in one state (Georgia). Since about 1910 parallel headway also was realized in some northeastern states and in California in selective drainage for the control of salt marsh and other sources of nuisance mosquito species.

The lining of small ditches to improve residual flows and to obstruct aquatic vegetation growth was first practiced for malaria control in the Panama program previously mentioned. Extensive adoption of this practice in the United States lagged until the mid-'30's, when its values were emphasized by the U. S. Public Health Service through Le Prince's work with state health departments and by demonstration at Memphis, Tenn. Installation of ditch lining and related measures have been limited largely to Federally financed activities (such as drainage at military installations, World War II), or to urban and suburban situations, because of their greater cost. In urban areas lining has found extensive application for beautification and nuisance mosquito control as well as for malaria mosquito control.

GENERAL PRINCIPLES OF DRAINAGE FOR MALARIA CONTROL

In malaria control practice the term *drainage* is broadly applied to all methods of water removal for prevention of malaria mosquito breeding. These include surface and subsurface (underground) drainage, filling (and appurtenant grading), and pumping. Although drainage for other purposes often results in malaria control benefit, most work of this type is designed principally for storm or floodwater protection, that is, municipal storm sewerage, highway and railroad drainage, stream flood-control drainage; or for agricultural irrigation. The problem of residual drainage (removal of quiescent water from the land and from open drainage ways) frequently is ignored in storm water design and construction practices through ignorance, oversight, or, even more commonly, to avoid added expense. At the other extreme, agricultural drainage for wet land reclamation seeks not only to remove surface waters but also to lower the ground water table well below the ground surface. Although this meets malaria control objectives, construction and maintenance costs are greatly increased. By contrast with storm water practice, drainage for malaria control primarily involves residual drainage which seeks (1) to remove quiescent surface water accumulations, both large and small; (2) to avoid the creation of similar surface water accumulations in the open man-made drainage systems; and (3) to accomplish these objectives at minimum expense and alteration of prevailing hydrographic conditions. Removal of storm and floodwaters is incidental and is attempted only where necessary to accomplish residual drainage. In general, other drainage objectives are restricted to multipurpose projects which include malaria control benefits.

To limit cost and increase effectiveness, malaria-control drainage should be applied selectively against the local anopheline vector of malaria. Generally, this can be accomplished at a small fraction of the expense of total mosquito control. The local prevalence of malaria governs the degree of malaria vector elimination necessary for suppression of the disease. Just as the breeding habits of the 20 or so principal anopheline vector species and malaria prevalence vary greatly, so do the strategy and tactics of drainage for malaria control. In fact, two important vectors in the eastern hemisphere breed only in running water, thus reversing for such areas "residual drainage" principles described in this chapter.

Consistent with engineering principles, drainage should be practiced only where it possesses advantage over other methods of controlling malaria. Potential advantages are:

1. Comparative and absolute effectiveness.
2. Comparative economy (in capitalized cost).
3. Comparative dependability.
4. Multipurpose benefits.

Drainage has its greatest application around population concentrations, principally urban areas. Even where breeding places are numerous, extensive, or both, rarely can it be justified in sparsely settled rural areas, although its role increases around rural communities, including plantations. Drainage as a sole method of control, however, is seldom justified in a control zone. Generally two or more methods are practiced. These should be complementary and should be selected following malariological studies, including appraisal of each principal breeding place or group of minor breeding places. Selection of too many methods in one control zone should be avoided, since this results in unnecessary duplication and dissipation of effort. Larviciding and drainage have particular complementary value. Frequently, drainage is selected for those breeding places in the control zone which are (*a*) close to affected human population (where complete elimination of breeding is indicated); (*b*) more distant but which are major sources of anopheline production, particularly those which cannot be larvicided effectively; and (*c*) particularly easy and inexpensive to drain. Larviciding would be practiced for remaining breeding places, particularly (*a*) outlying places where reduction rather than elimination of malaria mosquito production may suffice, (*b*) where breeding is light or sporadic, and (*c*) where drainage is particularly difficult or expensive.

The method selected for control of each breeding place (or group of breeding places) in the control zone should be carefully considered in relation to the over-all problem of reducing to a safe minimum at the least expense the number of adult vectors reaching human habitations. In view of the tactical character of malaria mosquito control, operations are often on a "cut-and-try" basis.

Limited drainage is practiced where obviously necessary, with all remaining breeding places larvicided temporarily. Larvae and adult vector collections then determine which additional places being larvicided should be drained.

DRAINAGE DESIGN AND PRACTICE

A few principles of drainage design and practice are listed in the following paragraphs. Further detail may be found in texts listed at the end of this chapter, in manufacturers catalogues and in trade association handbooks and brochures.

LOCATION AND LINE. Outlet drain location should be determined on bases of comparative cost, satisfactory grade and discharge point, soil stability, character of construction, and intervening breeding places to be drained along discharge line. Other factors being equal, straightness is desirable, but, where advantages accrue, the ditch line may be winding but not crooked. Curves should be on the longest convenient radii, and their outside banks should be protected against erosion where such flows are involved.

The location of collecting ditches within the watered area often is determined after the outfall ditch has "tapped" the pond and "pulled off" most of the water. In this way low spots are more easily found. Collecting ditches are run straight from low spots to the outfall ditch.

GRADE. Grades should be self-cleansing where possible, but not so steep as to develop eroding velocities. Permissible grade is a *function* of hydraulic radius, coefficient of roughness, character of soil, and erosion prevention features incorporated in the construction. In terms of soil character, a maximum grade of 1.5 per cent (0.015 slope) is permissible for small dry-weather flow-plain earth ditches in hard clay. At the other extreme stabilization cannot be achieved in a wet ditch in pure sand with a grade as flat as 0.05 per cent (0.0005 slope), in the absence of channel training revetment. For intermediate soil types (mostly sand clays and friable clays) the desirable grades for small dry-weather flow-plain earth ditches having bottom widths of 12 to 30 inches are in the range of 0.3 to 0.6 per cent, although as little at 0.05 per cent may be used in the absence of available fall at some increase in maintenance. Ditch checks for grade reduction (and appurtenant curtain walls) generally are introduced in such soil types for grades steeper than 0.6 or 0.7 per cent, or in flatter grades where storm water flows are encountered. As steep a grade as 5 per cent may be safely adopted without ditch checks, however, and in the presence of storm water flow, where small ditch sections are effectively stabilized with paved inverts, curtain walls, adequate bank sodding, and with aprons at cross drains, other constricted sections, and on the outside banks of curves. The most effective single stabilization and erosion prevention device is an adequate sod blanket on the bank.

The foregoing pertains to minor drainage, about which little is found in engineering texts. Major drainage when practiced for malaria control differs little from construction of this type for other purposes, except for the factor of preventing malaria mosquito production in the channel proper. An adequate and extensive literature exists in this field of engineering design and construction.

Cross Section. For malaria-control purposes only, the cross section and grade should be sufficient to accomplish drainage of the watered area within a week after maximum rainfall during the malaria season, that is, in less time than it takes a brood of mosquitoes to develop. Where storm water flows are relied upon to remove silt in ditches, the cross section may be enlarged somewhat, sufficient to induce a self-cleansing velocity throughout the length of the ditch. When drainage for malaria control serves other purposes as well, such as storm drainage, the cross-sectional area should be selected through reference to conventional runoff tables and local empirical experience.

Minor drainage ditches particularly should have narrow bottoms to improve the hydraulic radius at low flow. An ideal section for this purpose is the U bottom (Figure 32).

The Slope of the banks, under average conditions, is 1:1, that is one foot horizontally on each side for each vertical foot of depth. This will vary with the nature of the soil. In cuts through rock or hard clay, vertical walls are allowable and often preferable, whereas in sand clay, 1½:1, and in sand 2:1 or even flatter slopes may be required.

Steps in construction of a common type of ditch with 2-foot bottom width and 2-foot depth are indicated in Figure 33. The ditch is first dug to grade with vertical walls and full bottom width. Then the side walls are sloped 2 feet on each side giving a top width of 6 feet. If the ditch has a clear water flow, or self-cleansing grade, a cunette may be dug in the bottom to concentrate the dry

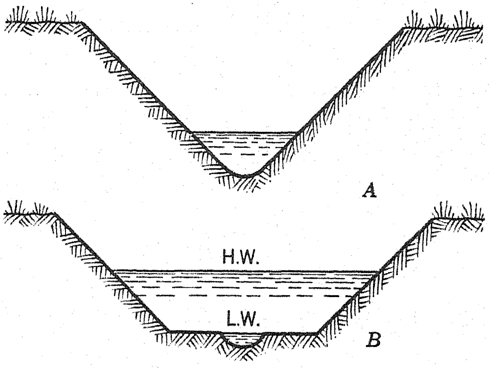

Fig. 32. *A* V-shaped ditch with U bottom.
B Inner drain in larger ditch.

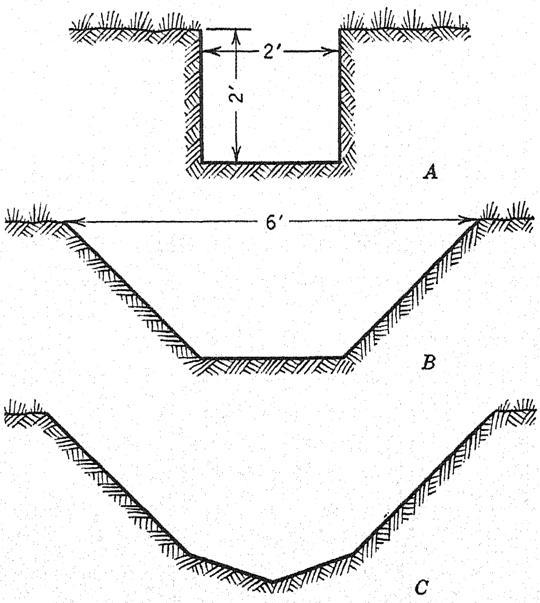

Fig. 33. Steps in construction of drainage ditch.

weather flow. Hand excavation to depths of over 4 or 5 feet requires rehandling of the material or the employment of hoists, both undesirable. Bulldozers, road graders, special ditch plows, and mule-drawn scrapers may be used profitably on many ditches which are finished by hand. Dynamiting by the propagation method is often the most economical method of constructing wet soil ditches of widely varying widths in cuts ranging from 2 to 6 or 8 feet, and is a useful auxiliary for stump and boulder removal from hand and power excavated ditches. The dragline is the most versatile piece of power equipment for malaria-control ditches exceeding 2 feet in bottom width and 3 feet in depth, except where rock is encountered.

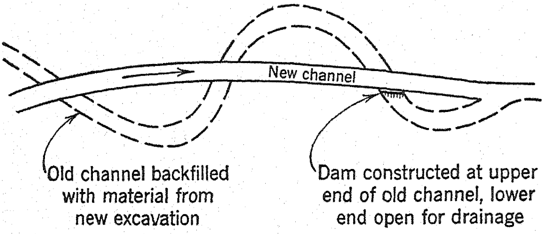

FIG. 34. Rechanneling a stream.

Spoil or excavated material should be spread evenly; or piled or banked well away from the ditch, preferably on the low side; or used to fill depressions. In large ditches the spoil should be piled 6 to 8 feet back from the edge so that it will not wash back into the ditch or exert enough pressure on the banks to cause slippage or landslides. If the spoil is left piled along the ditch, it should be cut through at regular intervals in flat terrain, or as the topography of the area indicates in rougher country, in order to let water drain into the ditch freely.

Lateral ditches should join the main ditch at an acute angle so that their flow comes in approximately parallel to and not across that in the main. This reduces turbulence and erosion and conserves grade. The lateral should also enter the main at a slight drop wherever possible, and its own grade should be increased slightly before the junction.

Rechanneling existing streams is frequently desirable in order to improve gradients by shortening distances. A straight channel is also more permanent. One which meanders tends always to increase the length of its loops by cutting away the outer banks and filling the inner. In cutting across existing meanders of the old stream there are two methods of treating the cutoff sections (Figure 34). They may be filled with excavated material from the new ditch or with other spoil or rubbish; or the upstream ends of each section may be blocked off leaving the remainder to drain into the new channel.

SEEPAGE. Seepage areas are created by emerging ground water and present a different drainage problem from that of other surface waters. These areas are of two principal types: those outcropping near the toe of abrupt slopes and generally having localized watersheds, and those fed from upwelling springs in flatlands. The latter are commonly supplied from more distant sources.

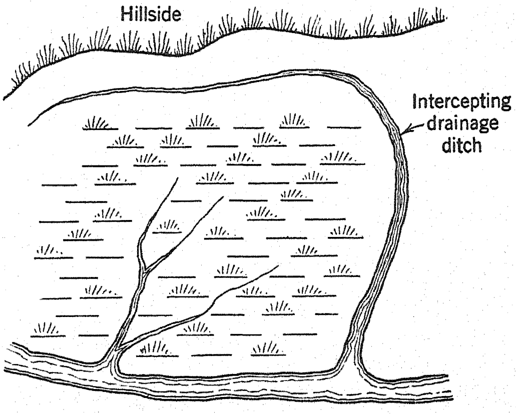

FIG. 35. Drainage for hillside seepage area.

The general rule in drainage for the first type of seepage area is to intercept the water strata on the slope above the seepage area with a shallow ditch, which is carried by the shortest route to a suitable discharge point. The ground water flow in the slope may be located by post-hole digger exploration. A typical slope interceptor ditch is illustrated in Figure 35.

Where the source of the ground water supply cannot be located through exploration, drainage of the watered areas follows surface drainage practices, except that lateral collecting ditches in the lowland often must be spaced more closely (Figure 36).

SUBSURFACE DRAINAGE. Subsurface drainage has many applications in malaria drainage practice, particularly where the malaria vector is predisposed to temporary and small accumulations of water, such as *Anopheles albimanus* production in hoofprints, wheel tracks, and other small puddles. Perhaps the major application is in conjunction with agricultural reclamation and irrigation. In some waste flatlands, especially those fed partly or wholly by seepage, an extensive system of shallow ditches may be necessary to remove surface water from relatively impermeable soils. Resultant conversion into pasture lands, or occasionally into cropland, would cause excessive maintenance costs if open drainage were used. Shallow covered "closed-drain" ditches overcome this problem at a significant added capital cost. In other instances, subsurface drainage is installed as an adjunct to irrigation; to reduce maintenance of open agricultural drainage ditches, facilitate agricultural management of the water, and prevent malaria mosquito production. A principal application in this field is for sugar cane irrigation, a crop requiring irrigation water for temporary periods in arid, and semiarid areas. Irrigation and abnormal rainfall waters must be promptly withdrawn after 1 or 2 days. Subdrainage systems accomplish this most effectively and in the long run most economically.

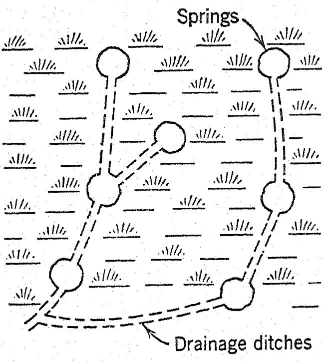

FIG. 36. Drainage for spring-fed marsh.

Other applications are to underdrain flat-grade wet ditches, in general, under ditch bottoms and in the sides of ditches where quicksand is a problem, and to permit the closing of small open collecting ditches, particularly in seepage areas. "Spring capturing," that is, sinking a length of large-diameter pipe vertically at a spring point with overflow through small-diameter subdrainage pipe to an outlet point, is another application.

The more common types of subdrainage are French drains and tile drains.

French drains are merely drainage ditches which have been filled with stone, logs, or other open material. The simplest type of underground drainage is one in which logs are placed in the ditch, covered with a filter of sugar cane trash, leaves, pine needles or other porous material and backfilled with the excavated material. Logs for this purpose should be 4 to 8 inches in diameter, piled in some such pattern as is indicated in Figure 37, and with their ends staggered. Wood will be preserved indefinitely under water, but near the outlet it is advisable to employ more permanent construction —stone or concrete. Loose rock makes an excellent French drain, where available.

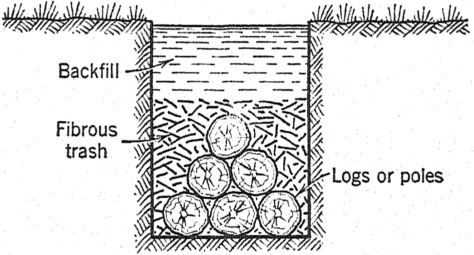

FIG. 37. French drain of logs or poles.

Tile drains, commonly employed in agricultural drainage, have also been adapted to mosquito control. These consist of butt-joint circular pipe 1 to 2 feet long and ranging in diameter from 3 to 15 inches (generally 4 to 6 inches); made of cement mortar, concrete, vitrified or hard-burned clay. In tight soil, drainage is improved by surrounding the joints with coarse aggregate. Vertical wells from top of ground to top of pipe made with a post-hole digger and backfilled with coarse aggregate are also helpful. The tiles must be laid on a carefully prepared bottom to preserve the grade and are butt-ended, with space allowed for the drainage water to enter. Occasionally, half-round tiles may be found equally efficient and more economical. When tile is used to underdrain open wet ditches, sand or sand–gravel is often used for the entire backfill (generally about 6 inches deep). To prevent washouts from storm flows, precast concrete curtain walls may be placed below grade across the ditch at spacings of 25 to 200 feet.

The field pattern may be either in parallel, or herringbone, with laterals converging to mains or subdrains, depending on topography and configuration of the area to be subdrained. Manholes for silt collection, cleanout, and inspection are provided at the junction points.

It is common practice for open systems of drainage to enter closed systems. Prime examples are open-field drainage ditches in the environs of cities, roadside ditches, and street gutters, which lead into main urban storm sewer systems. It is essential however, that the closed drainage system have a self-cleansing velocity or that the open ditch waters not be silt or trash-carrying. Since self-cleansing velocities are seldom encountered in flatland and subdrainage collecting systems, and pipe diameters are small and easily clogged, it is generally inadvisable to discharge open ditches into them.

The ultimate branches of the system are usually of 4-inch tile feeding into sublaterals of 6-inch and these into laterals of 8- to 12-inch. According to the area to be drained with the one system, the laterals may be collected into main drains of 24- to 36-inch pipe or open conduits.

PERMANENT OPEN DRAINAGE. During the construction of the Panama Canal from 1904 to 1910 Gorgas and Le Prince found that the cost of constructing permanent malaria-control ditches was less than the cost of maintenance in open earth ditches. Therefore, they paved the bottoms of malaria-control ditches with inverts. These inverts were of three main types:

Masonry, built of brick or stone set in mortar, particularly useful in ditches with steep gradients and considerable erosion.

Monolithic, in which concrete was poured between forms as a single unit.

Precast, built of short sections of concrete, cast and cured at a central factory, and laid in a ditch in which the subgrade had already been carefully prepared as to section and gradient. The precast inverts have become particularly popular, and many different patterns have been designed. The original design is called the *Panama invert.*

Figure 38*A* shows a typical cross section of a Panama invert with dimensions. Some ditches carry a large volume of storm water after heavy storms, but only a small amount of water normally. In such ditches the Panama inverts may be set in the middle of a ditch of broader cross section to carry the normal flow, with the bottom and sides of the larger ditch sometimes protected by shoulders of masonry or concrete on either side of the Panama invert, more or less a subditch in a main ditch as shown in Figure 38*B*. At times it is necessary to place side slabs above the Panama invert, sometimes two or three rows of such slabs on the outer side of steep curves, in order to prevent erosion. The banks of inverted ditches are protected by strip sodding or the planting of grass, such as Bermuda and Chinese centipede grass, above the inverts or side slabs in order to stabilize the banks and prevent erosion, side slippage, or undermining.

Tide Gates. Drainage presupposes a suitable hydraulic gradient from the collection area to the point of final discharge. Usually swamps are low-lying areas bordering water courses, occasionally covered by floods and normally wet because the soil is impervious and the terrain too flat to permit the free runoff of the rainfall. Spring-fed swamps have been referred to previously. In each case the water table remains at or above the surface, but drainage, though slow, is positive in the direction of some outlet at a lower level.

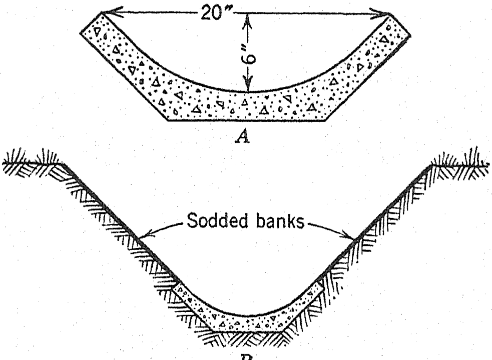

Fig. 38. Panama invert.

A Dimensioned cross section.
B As a subditch in ditch of larger dimension.

Marshes near the seacoast present a somewhat different picture. They tend naturally to build themselves up to about mean high tide and are overflowed regularly by the "spring" tides, each 14 days, and by any especially high tides due to storms. To be effective, drainage must be to a hydraulic grade somewhat below normal high tides.

Such marsh drainage involves diking the area to prevent the ingress of sea water and the provision of tide gates, which open to permit outward flow whenever the elevation of the water within exceeds that without and close automatically against any inflow from without. The principle of operation of the tide gate is illustrated in

Figure 39. Tide gates require frequent inspection and maintenance. They provide an economical means of drainage into tidal waters.

Pumps. It may be necessary to drain lands that are actually below the low-water level of adjacent watercourses. This requires providing a basin or sump into which the area can be drained and from which the water is removed by pumping. The western provinces of Holland represent an extreme case of this type of drainage. The Dutch windmills are not merely parts of a picturesque landscape. They make possible the drainage of the *polders,* the surfaces of which in many cases lie 10 or 12 feet below sea level. Their modern counterpart is the motor-driven pump which handles large volumes of water economically.

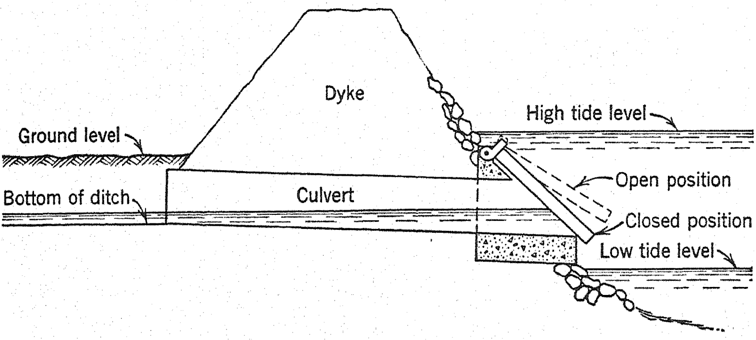

Fig. 39. Tide gate.

Pumping may also be required if the area to be drained lies at a considerable distance from the nearest available point of discharge, even though its elevation may be above that of the receiving body of water. It requires gradient to move water, and gradient involves distance as well as difference of elevation. Even though the water could be moved at low velocity in a large channel, it is economical at times to provide a higher velocity in a channel of smaller cross section leading into a low-level sump from which the water is then lifted by pumps to the discharge channel.

FILLING

Mosquito-breeding areas may be filled with dirt, rock, or rubbish. Although costly, except when performed incidental to other purposes such as spoil and waste disposal, filling has the advantage of tion is in and around urban areas where waste materials are more available, and appreciation in value of the reclaimed land often justifies substantial expenditure. Many cities now use the *land-fill* method of garbage and rubbish disposal (see Vol. 2), thus combining an important municipal function with the elimination of unsightly mosquito-breeding areas and the creation of valuable building lots or recreational areas.

Frequently it is possible to fill old ditches, stump holes, and small pockets along a drainage-canal right-of-way without any added expense by scattering the spoil from dragline excavation. Next to hydraulic filling, side slope grading (adjoining cut and fill), is the most economical filling method where conditions are applicable. Excavation and filling are performed in one operation by bulldozers, graders, and earth movers such as carryalls, where the average length of haul is within the range of 10 to 2000 feet. The cost of filling rises rapidly where earth must first be excavated by power shovel, then loaded, hauled and dumped by truck, and finally spread by bulldozer or grader.

Frequently drainage and filling are practiced as a combined method of dewatering an individual area, such as a pond. A long ditch 6 feet deep may suffice to reduce a 5-acre pond to a small pocket 2 feet deep. Filling of the pocket is resorted to as more economical than deepening the ditch another 2 feet.

Anopheline breeding in coastal and navigable waterways swamps is sometimes eliminated by hydraulic filling. Through the cooperation of river and harbor officials engaged in dredging channels or deepening harbors, it is sometimes possible to have the spoil from dredging operations deposited in nearby mosquito-breeding swamps, thus accomplishing two objectives at the same time, with little or no expense to the mosquito-control project. Since hydraulic dredgings usually contain a high percentage of colloidal material, there is a tendency for the spoil to crack badly as it consolidates. Salt marsh mosquitoes, especially *Aedes sollicitans,* sometimes breed in enormous numbers in the water collected in the cracks of such hydraulic fills. Some provision should be made in the mosquito-control budget to allow for harrowing the soil after it has dried and cracked.

YELLOW FEVER

aegypti, transmits the disease by biting an infected person within the first three or four days of the disease while the virus is still circulating in the blood. The virus multiplies within the mosquito until it has built up a sufficient concentration to be injected in infective doses into another human being. This incubation period in the mosquito normally lasts 9 to 12 or more days, depending largely on temperature. The mosquito remains infective throughout its life.

In man the incubation period is usually between 3 and 6 days. The *first stage* of the disease, lasting 1 to 3 days, is marked by sudden onset with severe head- and backache, prostration, high temperature, and high pulse. On the third or fourth day there is a *quiescent period* during which time there is temporary improvement. Then follows the dangerous *second stage* lasting 2 to 5 days with all the dreadful picture long associated with yellow fever or *Yellow Jack.*

The fatality rate ranges from 10 to 85 per cent with an average of 50 to 60 per cent in tropical epidemics. Patients who recover have acquired a life-long immunity.

HISTORY AND DISTRIBUTION

ORIGIN. It is probable that both the virus of yellow fever and the most common insect vector of the disease (*Aedes aegypti*) were brought to America in the days of the slave trade. Entomologically, it appears that *A. aegypti* is an importation into the New World, presumably as larvae in the water supplies of sailing vessels. There are no other species of the subgenus *Stegomyia* in America, although there are at least 27 species of this subgenus in Africa, some of which are efficient vectors of the jungle form of yellow fever, endemic over a large portion of tropical Africa. Carter, who has written one of the most comprehensive histories of yellow fever, believed that, although the biological evidence is not conclusive, yellow fever was of African origin. The historical evidence likewise substantiates such an assumption.

HISTORICAL. In 1881 Doctor Carlos Finlay of Havana, Cuba, first suggested that *A. aegypti* was the vector of yellow fever. He claimed that he had produced mild cases of the disease and conferred immunity upon the patients by feeding infected mosquitoes on non-immunes 2 to 5 days after the mosquitoes had ingested infected blood. Thus, the stage was set for the work of the U. S. Army Yellow

Fever Commission of 1900 and 1901 which finally demonstrated that the disease was caused by a filtrable agent and that the yellow fever mosquito was the vector of *urban* yellow fever.

This evidence was greatly strengthened by the work of Gorgas and Le Prince who demonstrated in Havana that yellow fever could be eradicated by rigorous mosquito-control measures. Later they were equally successful in controlling the disease in the Panama Canal Zone.

The phenomenal success in the control of yellow fever in these two areas, followed by the campaign of the U. S. Public Health Service in New Orleans in 1905, which stopped the epidemic before the first frost, and Doctor Oswaldo Cruz's successful campaign in Rio de Janeiro, led to emphasis on mosquito control during the following quarter century. Under the stimulus of the Rockefeller Foundation a concerted attack was made on yellow fever in South America with the result that the last American urban epidemics of magnitude were those which occurred in Rio de Janeiro, Brazil, in 1928 and 1929 when 435 deaths were recorded.

JUNGLE YELLOW FEVER. In 1929, just when it seemed as if the disease might be wiped off the American continents, leaving only a reservoir in the African stronghold, a severe epidemic occurred in Socorro in the mountains of northeastern Columbia. This epidemic, and one which occurred in the following year in Muzo, Columbia, were found to be quite different epidemiologically from the classical urban yellow fever transmitted by *A. aegypti*. Jungle mosquitoes (particularly *Aedes leucocelaenus* and *Haemogogus capricornii*) were found infected with the yellow fever virus in nature and were shown to be capable of infecting laboratory monkeys by biting. Two types of yellow fever were thus established: (1) an *aegypti*-transmitted type occurring in urban and rural areas where there are sufficient numbers of nonimmunes and *aegypti* mosquitoes to support the infection continuously; and (2) *jungle yellow fever* occurring in South America and Africa in which primates, edentates, marsupials, and rodents are the reservoir hosts and jungle-dwelling mosquitoes the vectors. Man is only occasionally an accidental host in this type of yellow fever, but once human cases have been contracted they can serve as foci for the epidemic *aegypti*-transmitted type of yellow fever. A third type of yellow fever denoted as "Nubian" has been found in the Nuba mountains of the Anglo-Egyptian Sudan. In this type, species of *Aedes* other than *aegypti* appear to be the principle vectors; man, the vertebrate host. The epidemic occurred in a rural region which differed in climate and fauna from the area in which jungle yellow fever usually occurs.

Distribution. Geographically, yellow fever is now found only in Africa and in Central and South America. It has never been found in historical times in Asia, Australia, or the Pacific Islands, although the yellow fever mosquito now occurs throughout all the tropical and subtropical parts of the world. Europe has had repeated epidemics from 1730 to 1890, but no recent outbreaks of the disease have been recorded. In the United States yellow fever has been found throughout the southern and eastern part of the country; from the Gulf states north to Missouri, Illinois, Indiana, New York, Vermont, and New Hampshire. The last important epidemic in the United States was the New Orleans outbreak of 1905. Epidemics have been reported from the West Indies, Central and South America south to Argentina, Paraguay, and Peru. Jungle yellow fever is still endemic in South America north to Panama and in tropical Africa.

YELLOW FEVER CONTROL

At the present time extensive reservoirs of yellow fever exist in Africa and South America, either as the classical *aegypti*-transmitted yellow fever, as jungle yellow fever, or as Nubian yellow fever. The mosquito vector, *A. aegypti,* is widely distributed in every tropical and subtropical country where it lives by preference near or in human habitations and feeds on human blood. The only essential lacking to start epidemics in many parts of the world is the virus. In these days of rapid airplane travel this may be introduced at any time, either in an infected mosquito or in a patient coming down with the disease. In order to achieve control from a public health viewpoint a number of procedures are available.

Quarantine. Quarantine of airplanes traveling from endemic to uninfected areas is practiced extensively at the present time. In the great movement of troops back from Europe at the end of World War II, the Army established a huge insecticiding program designed especially to prevent entrance of the dreaded malarial mosquitoes, *Anopheles gambiae,* from Africa into the New World and to prevent mosquitoes possibly infected with yellow fever virus from being transferred from either Africa or South America into countries free from this disease at the present time. Planes are sprayed with insecticides at Natal and Belem in Brazil, in British Guiana, Trinidad, Puerto Rico, and Miami, Fla. The procedures follow somewhat those worked out by U. S. Public Health Service for the disinfection of commercial aircraft such as the Pan-American airplanes. Similar precautions to prevent the introduction of yellow fever from Africa into India are practiced, the planes from the West arriving at Karachi and being insecticided there.

Quarantine of apparently uninfected human beings from endemic areas is seldom practised. Such persons from endemic areas are kept under surveillance by state, municipal, or county health officers for 9 days—this period covering six days of incubation in man and 3 days of infectivity to mosquitoes.* In actual epidemics yellow fever patients are kept under mosquito bars for at least the first four days of the disease, preferably longer, in order to prevent mosquitoes from biting the patient and becoming infected with the virus.

VACCINATION. One of the major developments in yellow fever control has been the production of a yellow fever vaccine consisting of a desiccated preparation of living attenuated yellow fever virus. Injections with this vaccine are said to produce a mild case of yellow fever which confers lasting immunity to strains of the virus from widely separated areas of the world. At the present time the U. S. Army and Navy and many governmental and private agencies require yellow fever vaccination for all personnel living in yellow fever areas.

AEDES AEGYPTI CONTROL

A. aegypti control in connection with the eradication of yellow fever dates from the historic campaigns of Le Prince and Gorgas in Havana, Cuba, and, later, in Panama during the building of the Canal. The remarkable sanitary campaign of Doctor Oswaldo Cruz in Rio de Janeiro, Brazil, was so successful that it led to the belief that yellow fever might be eradicated from the world by a vigorous attack on the urban centers of the disease. In the period 1926 to 1932 there were progressive improvements in the campaigns conducted by the Brazilian Government and the Rockefeller Foundation,

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* A detailed account of this procedure is given by C. L. Williams, *Am. J. Trop. Med.*, 24, 245, 1944.

incorporated as the Yellow Fever Service of Brazil. This organization has achieved such great success in its campaigns that it has become the model of most modern yellow fever control agencies.

THE BRAZILIAN PLAN.* The Brazilian plan is based upon the idea that there is a fundamental distinction between control measures designed for an emergency outbreak of yellow fever and those for a long-range public health campaign. In checking the outbreak all available means of control should be used to stop the epidemic as soon as possible: such methods as quarantine, vaccination, killing of all stages of *A. aegypti,* including fumigation and insecticiding for adults and particularly the elimination of larval breeding places.

In the long-range program a different approach is necessary both from the operational and financial viewpoint. The goal is complete *aegypti* eradication—not merely from a single city or county, but from a whole country or continent. Control campaigns in widely separated areas have shown that the reduction of *aegypti* breeding to a point where yellow fever disappears from a community is relatively easy, but the complete eradication of the species is difficult. "The experience of the Yellow Fever Service in Brazil shows that *aegypti* breeding cannot be controlled economically by the time-honored methods of simply reducing the intensity of such breeding; only when species eradication, beginning in the larger centers, is carried to the smaller towns, villages, and even rural districts of the surrounding areas, which would otherwise reinfest the larger centers, can *A. aegypti* be controlled at little cost. . . . Theoretically, anti-*aegypti* measures should be easy, since the breeding foci of this mosquito are generally limited to artificial containers, in, and in immediate proximity to, human habitations. In practice, the discovery and elimination of the final traces of *aegypti* breeding are often difficult, not only because of the instinctive wiles of the *aegypti* mosquito, but because of the public relations and personnel problems inherent in any attempt to apply routinely even the simplest measures in hundreds of thousands of homes."

The permanent long-range program against *A. aegypti,* as worked out in Brazil, is applicable to yellow fever or dengue control throughout the tropics and subtropics, and also in temperate countries such as southern United States.

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* F. L. Soper, D. B. Wilson, S. Lima, and W. Antunes, *The Organization of Permanent Nation-Wide Anti-Aedes Aegypti Measures in Brazil,* Rockefeller Foundation, New York, 1943.

There is, first of all, an initial cleanup campaign for the elimination of all easily accessible *aegypti* foci. This is directed primarily against larval breeding places in water kegs, cisterns, fountains, receptacles in cemeteries, and other artificial containers holding water such as collections of old automobile tires, and sometimes collections of old bottles or tin cans. Insofar as possible an effort is made to empty all such water containers, either by turning them upside down, or by making a hole in the bottom. When this is not practical, they can sometimes be filled with sand as is the case with flower vases and urns in cemeteries. Abandoned wells and cisterns are closed completely with stone or brick and mortar, or cement. Wells or cisterns in operations are covered with tightly fitting screened covers which will allow entrance of light, water, and air, but will exclude the mosquitoes. Stacks of automobile tires are sprayed from the top with pure Paris green, the fine dust settling within the tires where it remains for a long time as a stomach poison in any water collections.

After the first big reduction in the numbers of adult *aegypti* has been made, the patient time-consuming discovery and elimination of hidden inaccessible breeding places is begun. This involves oiling or destruction of all containers in which *aegypti* larvae or pupae are found. In this phase of the work chief reliance is based on adult capture surveys by trained inspectors. These men, who are experts at discovering living *aegypti* adults, then proceed to search out the larval and pupal breeding places, because it has been found that under normal conditions the *aegypti* adult lives only a week or two and seldom flies much more than 100 yards from its breeding places.

In many tropical countries top minnows (*Gambusia affinis*) are grown in specially constructed fish ponds on government property. They are distributed by trained inspectors and are of some use in controlling breeding of *Aedes aegypti* and *Culex quinquefasciatus* in such places as cisterns, lily ponds, and fountains.

In the Brazilian plan of eradication there is also permanent maintenance of a sentinel service to discover and eliminate any reinfestations of *aegypti* which occur. Ben Franklin's old adage that "A stitch in time saves nine" finds its counterpart in this phase of eradication. The killing of a single gravid female at this stage of the campaign may prevent reinfestation of a large zone in which *aegypti* have been eliminated at considerable expenditure of money, labor, and time. *A. aegypti* has an enormous reproductive capacity, with its large number of eggs laid, its relatively short life cycle (average about 2 weeks from egg to egg), and hence its large number of generations per year.

One of the most potent forces in reducing the menace of both yellow fever and dengue has been the installation of adequate municipal water systems in many large tropical and subtropical cities, thus doing away with the jars, barrels, and tanks in which potable water was stored and *aegypti* larvae and pupae formerly bred.

DDT is a most effective insecticide to use in controlling *Aedes aegypti*. This insecticide is applied especially to the surfaces of domestic water containers, whether empty or full. This procedure converts these breeding places into lethal traps for the egg-laying females. Moreover, any larvae hatching from eggs laid in these jars are killed by the residual DDT action as soon as the container is filled with water.

DENGUE

Dengue is a comparatively mild disease which, like yellow fever, is transmitted by *A. aegypti* and certain other species of the same genus. Both diseases are caused by filterable viruses and have about the same incubation period and the same type of fever. The fatality rate of dengue, however, is low, and an attack does not confer lifelong immunity.

The mosquito must bite a dengue patient during the first 48 hours of the disease in order to become infective. Then begins the *extrinsic incubation period* in the mosquito during which time the virus multiplies throughout the entire mosquito body until it becomes of such concentration as to allow injection of an infective dose into man. This incubation period in the mosquito lasts 9 to 14 days or more, depending chiefly on temperature, after which the mosquito remains infective for life.

In man dengue usually lasts about a week, giving it the name *seven-day fever*. It is characterized by an initial period of 3 or 4 days with high temperature, marked soreness in the joints and bones (thus giving it another common name—*breakbone fever*). A fine reddish rash usually appears about the third or fourth day and begins to disappear on the fifth to seventh day. In some cases there is another rise in temperature accompanied by general malaise during the last 2 or 3 days. Fatalities from dengue are quite low, usually less than 1 per cent in epidemics except among very young children and old people where the cases are complicated. It has been an important disease in the Pacific warfare during World War II because it can affect such a large portion of the troops almost overnight, incapacitating them for a week or more. At Tulagi, it is reported, almost all the troops were affected soon after the cessation of the ground action at that base early in August 1942. At Espiritu Santos 12 to 40 per cent of individual commands had dengue within a 3-month period. In some of these epidemics there is a possibility that a jungle mosquito, *A. scutellaris hebrideus,* was the vector.

DISTRIBUTION

Unlike yellow fever, which is confined today to the tropical parts of Africa and the New World, dengue occurs throughout the tropical and subtropical parts of the world following the distribution of *A. aegypti* and *A. albopictus*. Epidemics have occurred in the Gulf States and along the Atlantic Coast north to Philadelphia. Dengue, or denguelike fever, is endemic in the West Indies and South America as far south as Sao Paulo, Brazil. Hawaii had a serious epidemic in 1943 and 1944. Dengue has plagued Anglo-American troops fighting in the Pacific Islands from Australia and New Guinea north to the Marianas. It is common in the Mediterranean area, particularly in Greece and Egypt, where in 1927 and 1928 a million and a half people were said to have been attacked.

DENGUE CONTROL

The routine measures mentioned in the section dealing with yellow fever control will usually prevent dengue if *Aedes aegypti* is the vector. However, in a considerable portion of the world *A. albopictus* and several species in the *A. scutellaris* complex have been incriminated as vectors of dengue. These mosquitoes breed in rain barrels and other collections of water near human habitations, and also in such places as tree holes and coconut shells in the jungle. Such breeding places are oiled or destroyed, whenever possible. In areas where these measures are not practicable, control has been obtained by spraying with DDT, in Diesel oil or kerosene, dispersed from low-flying airplanes.

PLAGUE

Plague is an acute infectious disease caused by a bacillus, *Pasteurella pestis*. It is primarily a disease of rodents, in which it occurs in either of two types, *bubonic* and *septicemic*. Rodent fleas which have ingested plague bacilli while feeding on their host leave the rodent when it dies and attack man, thus transmitting the disease to human beings. The primary reservoir of the disease is the so-called *sylvatic plague* of wild rodents, such as the *tarbagan* of Manchuria and more recently the *ground squirrels* of western North America. It is believed that domestic rats become infected from these wild rodent reservoirs and then carry the disease from country to country along the highways of commerce. The last pandemic of plague supposedly originated in a sylvatic plague region of Yunnan Province, China, and reached the seaports of Hongkong and Canton in 1894. From these ports it was carried by plague-infected ship rats and rat fleas to India, Africa, the Philippines, and Australia; it reached South America in 1899 and San Francisco, Calif., in 1900.

TYPES OF PLAGUE

There are three major types of plague distinguished by the localization of the acute infection. The *bubonic* type is localized in the lymphatics and may produce the characteristic swellings or *buboes* in the groin, armpits, and neck region. The period of incubation may be as long as 2 weeks. Fatalities range from 25 to 90 per cent.

The *septicemic* type is characterized by massive infection of the blood stream with the plague bacilli, either by drainage from a bubo or by primary inoculation through the mucous membrane. It is practically 100 per cent fatal.

In the *pneumonic* type the acute infection is localized in the respiratory system. This may be the end product of an original bubonic type or secondary to the septicemic type, or it may have been contracted directly by droplet spray infection; the sputum of patients with pneumonic plague is always heavily infected with the bacilli. The period of incubation may be as short as one day, and the fatality, as in the septicemic type, is practically 100 per cent.

HISTORY

Plague is a disease of great antiquity, having been known since Bible days under such names as *the black death* or *the pest.* It was during the pandemic at the end of the Middle Ages that the Venetians introduced the practice of quarantine, keeping strangers from plague infected areas in lazarettos for 40 days, presumably on some island near Venice. The plague epidemic in Florence (1348–53) led to the isolation of the group of people who are supposed to have told the classical collection of stories in Boccaccio's *Decameron*. Manzoni's great historical novel, *The Betrothed,* gives a vivid account of conditions in Italy at this time. The historic outbreak in London in 1665 has been recorded in Defoe's *Journal of the Plague Year* and in Samuel Pepy's *Diary*.

GEOGRAPHICAL DISTRIBUTION

At the present time heavy endemic foci of human plague are known to exist in Manchuria, China, Indo-China, Java, British East Africa, and north Africa. Sylvatic plague in rodents exists in Mongolia and Manchuria, Belgian Congo and South Africa, parts of South America, and western United States. Sylvatic plague in rodents was not discovered in California until 1908, 8 years after plague was first discovered in San Francisco. It is assumed that the ground squirrels in the Far West were uninfected with plague until after the San Francisco outbreak in 1900. By 1947 plague-infected rodents had been found in 14 states between the Rocky Mountains and the Pacific Coast and even as far east as North Dakota, western Kansas, and western Texas. Epidemics of plague in man are commonly preceded by epizootics in rats, but human outbreaks in Manchuria, Argentina, and South Africa are said to have been caused directly by wild rodent fleas.

PLAGUE TRANSMISSION

As the result of the work of many investigators about the turn of the century, it was definitely shown that fleas had a direct role in the transmission of bubonic plague from rodent to rodent, and from rodent to man. Human infections may result from the bite of a flea or by the later introduction of infectious material into a scratch or other skin abrasion. The feces of an infected flea, defecated as the insect feeds, are heavily laden with the plague bacilli. The flea may also become *plugged* or *blocked* by a mass of blood and bacilli in the mid-gut, causing it to regurgitate its blood meal, laden with bacteria, during feeding.

PLAGUE CONTROL AND PREVENTION

QUARANTINE. International quarantine regulations were established during and following the last great pandemic of 1894–1905. These provide that all ships from epidemic areas be quarantined at ports of entry until the danger of introducing the disease is past, that all ships be fumigated with hydrocyanic gas or sulphur to kill all rats and rat fleas aboard, and that rat guards, large circular disks of galvanized metal, be set on all ropes by which a ship is moored to the dock in order to prevent rats leaving or entering a ship. Since the incubation period of plague in human beings may last 10 days or more, individuals should be held in quarantine for at least 10 days after leaving hyperendemic areas. It is also known that plague bacilli are present in the bodies of convalescents. Such people should be isolated for a month before being allowed to live in an uninfected populace.

RAT PROOFING AND RAT ERADICATION. As soon as it became known that rats and rat fleas were the primary reservoir of plague, rat control became one of the most important parts of plague-control programs. Such a project involves garbage removal to eliminate the chief source of rat food, and rat proofing and rat eradication by fumigation, poisons, and trapping. These methods are discussed in detail in Volume II. That rat proofing and rat eradication are effective in controlling plague epidemics was clearly demonstrated by the campaign of the U. S. Marine Hospital Service in San Francisco in 1900 and of the Public Health Service and local state and municipal health departments in the New Orleans and Puerto Rican campaigns.

IMMUNIZATION OF HUMAN POPULATION. Early in the Bombay epidemic at the turn of the century, Haffkine succeeded in making a prophylactic inoculation which was of great value in reducing both the number of cases of plague contracted and the mortality among plague victims. His method consisted essentially of subcutaneous injection of cultured plague bacilli which had been killed by heat and treated with carbolic acid. Strong first used living avirulent plague bacilli for vaccinating against plague in the Manchurian epidemic of 1907. More recently de Vogel and Otten in Java have practiced mass vaccination with living avirulent plague bacilli. They claim to have vaccinated over two million Javanese without incident or accident and believe that this vaccine has played a major part in limiting the present plague epidemic in Java which reached its peak in 1934.

TYPHUS FEVER

There are two main types of typhus fever: the classical *European, epidemic typhus* which is transmitted by the body louse (*Pediculus humanus*), and the *murine, endemic typhus,* transmitted by the rat flea. Both belong to the group of infectious diseases known as *rickettsial diseases.*

RICKETTSIAE

Rickettsiae are microscopic organisms not definitely referable to either the plant or animal kingdoms. They resemble viruses and some protozoa in being able to live only in living cells, but differ from viruses in being too large to pass through a Berkefeld filter. Morphologically they resemble diplococcoid bacteria, varying from almost invisible particles to intracellular bodies 2 microns in length. They can be stained by protozoan stains and are Gram-negative. So far as is known at present, rickettsial diseases are transmitted only through the bite of an infected arthropod (such as a tick, mite, or louse) in which the rickettsiae have undergone some cyclical changes, or through the scratching in of infected arthropod feces dropped by the animal during feeding. Rickettsiae are the causative agents of three great groups of human febrile disease: (1) the typhus group, (2) the Rocky Mountain spotted fever group, and (3) the Japanese river fever or tsutsugamushi disease group. Because of its widespread distribution and its high mortality in large population groups, public health officials have been concerned mostly with typhus fever control.

EPIDEMIC TYPHUS

Description. Epidemic typhus is an acute infectious disease transmitted from man to man by the louse (*Pediculus humanus*) and caused by *Rickettsia prowazeki* (named in honor of the two scientists, Ricketts and Prowazek, both of whom died while studying rickettsial diseases). In man the incubation period lasts from 6 to 14 days after he has been bitten by an infected louse. The sickness begins with an abrupt sustained elevation of temperature, marked prostration, and body pains. Then follows the stage of the eruption often accompanied by marked mental and nervous conditions. In uncomplicated cases the patient may be well 2 or 3 weeks after the onset of the fever.

The classical louse-borne typhus has been one of the major epidemics of the world. Epidemic typhus has been reported from Europe, the northern half of Asia, most of Africa, South and Central America, and in the 19th century from North America. The last important epidemic in United States occurred in New York City in 1892. In peacetime, under the impetus of generally improved living conditions and better diet, typhus recedes to its two main foci in central Europe: Soviet Russia and Poland, and the Balkan countries. But under war conditions, with fewer sanitary facilities, poorer diet, and large masses of people living under crowded conditions, typhus increases rapidly and takes a heavy toll of human life. In World War I some 10,000,000 Russians are said to have had typhus, of whom 2,000,000 died. In the Serbian epidemic of 1915, out of some 460 Serbian doctors attending the sick, three quarters came down with typhus, and more than 120 of these died from the disease.

LIFE HISTORY OF THE BODY LOUSE. Body lice, also known as *cooties* and *seam squirrels,* have only three developmental stages: egg, nymph, and adult. The eggs are cemented to body hairs or to fibers of clothing, particularly in the seams. Normally they hatch in about 8 days. Under optimum conditions there are three molts 2 to 3 days apart; thus the life cycle from egg to adult requires 2 to 3 weeks. The eggs are laid a day or two after the lice become adult. Lice are transferred from one person to another by direct contact or contaminated clothing or bedding; quite frequently, by exchange of blankets or clothing infested with lice eggs.

CONTROL OF EPIDEMIC TYPHUS. In epidemic typhus, control measures are directed largely towards eradication of lice in clothing and personal effects and to thorough delousing of all individuals. During World War I epidemic typhus raged on the eastern front and in the Balkans, and the louse-borne disease, trench or Wolhynia fever, incapacitated thousands on the Western Front. It is a high tribute to the efficiency and thoroughness of the medical and sanitary corps of the German Army in delousing soldiers and equipment being transferred from the eastern to the western fronts that no serious outbreaks of epidemic typhus occured in either German or Allied armies on the western front.

An extensive account of methods of delousing and disinfestation is given by Dunham: practical methods of delousing men and materials, ranging from the Serbian barrel for a small group of soldiers to fixed installations complete with steam and hot-air sterilizers, dressing rooms, showers, and barber shops with a capacity of several thousand a day at a port of embarkation. Basically, however, the idea is the same in any type of delousing. Lice and their eggs are killed in 1 minute when subjected to dry heat at a temperature of 155 degrees Fahrenheit, or in 5 minutes at a temperature of 131 degrees Fahrenheit. Immersion in boiling water for 30 seconds will kill both lice and their eggs. Steam sterilization is the most common and convenient type to use. It has the disadvantage, however, of wrinkling woolen clothes and making them difficult to press afterwards. It may also seriously damage articles made of leather, felt, or webbing. Dry heat does not harm leather, felt, or webbing, but it may harm woolen fabrics if the temperature gets too high. It is very difficult to regulate the temperature with the dry-heat method or to obtain proper penetration of the hot air to all parts of the clothing and articles being treated.

Disinfestation may be accomplished simply by storing infested clothing and equipment, thus depriving lice of their human blood supply. The nymphs die in about a day or two, and the adults in 10 days to 2 weeks time, but the eggs may not hatch for nearly a month if the clothing or bedding is not used. If infested material can be stored for a month or more, disinfestation can be obtained with a minimum effort and expense.

Personal delousing is usually done while clothing and equipment are being disinfested. The hair and most of the body are scrubbed with 10 per cent acetic acid to loosen and remove the eggs, followed by a shampoo with hot soapy water and kerosene to remove the eggs and kill the nymph and adult forms. Whenever possible, the individuals should be given a short haircut and a smooth shave to remove the head lice as well as body lice.

Modern control of epidemic typhus is best exemplified in the now historic campaign carried out in Naples, Italy, during the early part of 1944. When the city was captured by Allied troops in 1943, epidemic typhus was rampant in the native population which had been living for months in air raid shelters and ruined buildings. Within 3 months this raging epidemic was brought under control by the United States of America Typhus Commission using two new weapons which promise much for the future happiness of the world.

Mass delousing was practiced by blowing DDT insecticidal powder into clothes through open sleeves, necks of shirts and dresses, or tops of pants and skirts. Delousing stations were set up all over the city, and it was made obligatory to go through such stations before boarding a train. It is estimated that over 1,300,000 persons (more than the peacetime population of Naples) were treated in this manner during 2 months. The DDT powder had a lasting effect up to 6 weeks in clothes, beds, and personal effects. Even after laundering, lice and other parasites were killed by the DDT, which is an effective contact insecticide in almost infinitesimal quantities. Mass vaccination was also employed by injecting a chick embryo vaccine, first made by Doctor Herald Cox of the U. S. Public Health Service.

ENDEMIC TYPHUS

Murine or endemic typhus is similar to the epidemic form, but, although milder, is still a severe illness. The true fatality rate is probably 1 to 5 per cent. The acute stage probably averages about 2 weeks, but the period of recovery is frequently several months. It is usually stated that the chances of recovery are good unless the patient is more than 60 or less than 10 years of age, or debilitated.

History. As a result of the studies and typhus-control campaigns conducted during and following World War I, it was rather widely accepted that lice were the sole vectors of typhus. However, isolated mild cases of typhus in southeastern United States led to studies by the U. S. Public Health Service which indicated that endemic typhus is a distinct type of typhus differing in its epidemiology from the classical epidemic form. One major point of distinction is that it is transmitted by the rat flea and possibly by mites.*

Murine typhus has since been shown to occur in the Mediterranean region, and in Asia, Andean South America, Mexico, and the southern United States. During 1944 over 5000 cases were reported in the United States, where it is most common south of a line drawn at the level of the southern boundary of Tennessee and especially prevalent in the states of Texas, Georgia, Alabama, and Florida. In some areas of the deep South murine typhus is both

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* K. F. Maxcy, *U. S. Pub. Health Service, Pub. Health Repts.,* **41**, 2967, 1926. R. E. Dyer, *op. cit.,* **46**, 334, 2481, 1931.

an urban and rural disease, owing to widespread typhus infection in both urban and rural rat populations. Farther north typhus infection in rats tends to be limited to rat colonies in business establishments.

TRANSMISSION. The causative organism of endemic typhus, *Rickettsia mooseri,* may be carried from rat to rat by the plague flea (*Xenopsylla cheopis*), the rat flea (*Ceratophyllus* or *Nosopsyllus fasciatus*), the rat louse (*Polyplax spinulosa*), and the tropical rat mite (*Liponyssus bacoti*). Transmission from rat to man is probably effected by the two fleas: *Xenopsylla* in the tropical countries and cities, and *Nosopsyllus* in the more temperate climate. Lice, infected with the rickettsiae of epidemic typhus, die in about 11 days, but rat fleas infected with the rickettsiae of endemic typhus will live and remain infected for months. The actual transmission from flea to man probably takes place either through flea bites or by the entrance of infected flea feces, defecated during feeding, into scratch wounds.

CONTROL MEASURES. The control of endemic typhus, like that of plague, is directed towards the elimination of rats and rat fleas. Rat control is discussed in Volume II.

One of the most recent developments in plague and typhus control is the use of DDT to kill rat fleas. This method attempts to break the chain of transmission by attacking the rat flea, vector of both murine typhus and plague, instead of following the routine method of eradication or elimination of rats. It has been found that DDT powder kills rat fleas in 24 hours but has relatively little effect on the rat mites or lice. Ten per cent finely ground DDT in powder is recommended. Its effectiveness as a method of murine typhus control is under extensive trial.

BEDBUGS

Although bedbugs live in intimate association with man throughout the world from the Arctic to the tropics, there is no conclusive evidence that they are vectors of any human disease-causing pathogens. Bedbugs are, however, most annoying and persistent pests and most difficult to control. They are particularly annoying and abundant in places where people must live in close association with one another, such as in jails, barracks, or ships' quarters. Some people show no reaction to bedbug bites and apparently are hardly aware of being bitten, while others have marked swelling and itch-ing, lose sleep, and become nervous as the result of continued bites by bedbugs.

Two species of bedbugs are common: *Cimex lectularius* which occurs in the temperate and cold regions of the world, and *Cimex hemipterus,* the tropical bedbug. Both species are reddish-brown insects about a fifth of an inch long, wingless or with tiny stubs of the forewings and a strongly flattened abdomen. The eggs are laid over a long period of time in a great variety of places, such as beds or mattresses, or in cracks of furniture or the floor, or under wallpaper. The eggs, which are glued to the surface upon which they are laid, hatch in 6 to 30 days. The young are called nymphs and resemble the adults considerably (in contrast to the larvae and pupae of mosquitoes which bear no resemblance to the adults). The post-embryonic stages may be completed in as few as 29 or as many as 139 days depending considerably on temperature and food. There are five molts, a blood meal being necessary before each molt. Breeding is continuous throughout the year, with at least three or four generations a year.

CONTROL. Light infestations may be controlled by thorough spraying with kerosene, gasoline, or some of the better fly sprays such as the pyrethrum–kerosene mixtures, especially if particular effort is devoted to all cracks and crevices in walls, floor, and furniture. Careful, persistent spraying will frequently keep a slight infestation from becoming general or severe, and may eventually eradicate the bedbugs.

General or severe infestations can be controlled by fumigation or by use of dry heat. In either method one of the most important parts of the work is the proper preparation of the building, such as sealing all cracks and openings, doors and windows (except the door through which the operator is to leave).

FUMIGATION. *Hydrocyanic gas, sulphur dioxide,* and *methyl bromide* are the gases most commonly used in the fumigation of buildings. *Hydrocyanic gas is a deadly poison and must be handled with extreme care by a responsible and experienced person.* Hydrocyanic gas is available in several forms: Zyklon, HCN discoids or liquid hydrocyanic acid. It may be generated from cyanide "eggs" and acid in earthenware containers. At least two ounces of HCN should be applied per 1000 cubic feet of space, and the minimum time of fumigation should be 4 hours, preferably longer. Zyklon is an earthy compound impregnated with liquid hydrocyanic acid.

It comes in sealed containers and may be sprinkled on the floor. HCN discoids are made by forcing hydrocyanic acid and 5 per cent chloropicrin into disks of wood pulp. They are very convenient to use, since it is possible to distribute a given number on the floor of a building, or to toss an estimated quantity into a ship's quarters, in a very short time before sealing the entry way. After 2 to 4 hours the gas is liberated from the discoids, and they are then non-poisonous. Liquid hydrocyanic acid is available in steel cylinders as a liquid under pressure which vaporizes at a temperature of about 74 degrees Fahrenheit. It is frequently used in ship fumigation.

One of the first and still most commonly used methods of fumigation with HCN is by the so-called "pot fumigation." The dosage of HCN gas needed is calculated, and the cyanide "eggs" are put in paper bags beside the earthenware crock containing the calculated amounts of water and sulphuric acid. Then, starting on the upper floor or farthest from the door in a one-story building, the bags are dropped in the pots to generate HCN, and the operator leaves the room as quickly as possible. The building should be tightly closed for 4 to 6 hours, with a guard posted at the entrance to the building. At the end of this period the building is opened and *thoroughly ventilated* before being occupied.

DRY HEAT AND COLD. The use of dry heat affords a simple and reliable method of ridding a house of bedbugs. If a building can be kept at a temperature of 120 to 140 degrees Fahrenheit for a few hours, all stages—eggs, nymphs, and adults—will be killed. Conversely, in winter if a building can be left open to the elements so that the cold penetrates to all parts of the building, a temperature of 0 degrees Fahrenheit or below will kill all stages in a few hours.

DDT. The most recent development in bedbug control, and one of the most promising and easy of application, is the use of DDT as a residual spray. A single thorough application of 5 per cent solution of DDT in kerosene or in emulsion form will eradicate bedbugs for more than a year. The kerosene solution seems preferable because it lasts longer and is more adhesive. Approximately half a pint solution is used per bed with a dosage of about 200 milligrams of DDT per square foot for flat inside surfaces such as walls or floors. The residual action of DDT is important in controlling bedbugs. It not only kills the adults and nymphs present at the time of spraying, but also remains as a fine layer of crystals on whatever surface it is sprayed and is toxic to insects walking over these crystals for weeks or months after the original application. Nymphs which hatch from eggs after a building has been sprayed with DDT or adults which have been introduced from the outside cannot cause reinfestations as long as the chemical remains active. DDT residual spray applications are especially important in controlling insects in barracks and houses which cannot be fumigated because their construction does not allow their being made gastight.

THE HOUSEFLY

The housefly (*Musca domestica*) has been called the most important single insect in the world from the viewpoint of public health, because of its widespread distribution from the tropics to the Arctic and the number of human pathogens which it can carry.

During the Spanish–American war definite proof of the fly-borne origin of the typhoid fever oubreaks in the American Army camps was obtained when flies, carrying particles of lime from the open latrines, were found repeatedly in the kitchens and dining rooms. Cultures from these flies were positive for typhoid fever and other human pathogens carried mechanically on the flies' sticky feet or proboscis, or as vomitus or feces from its alimentary canal.

The diseases mechanically transmitted in this way by flies belong largely to the enteric group. Experimental and epidemiological evidence has incriminated the housefly as a vector of the following:

Typhoid (*Eberthella typhosa*), paratyphoid (*Salmonella paratyphi*), bacillary dysentery (*Salmonella enteriditis and Shigella dysenteriae*), cholera (*Vibrio comma*), and amoebic dysentery (*Endamoeba histolytica*). In addition, flies may carry helminth eggs (*Ascaris,* etc.). Recently attention has been focussed on the housefly as a possible vector of poliomyelitis in rural areas as well as in cities where sewage carrying the polio virus is discharged without treatment into streams or lakes. Of the nonenteric diseases, flies have been suspected of a role in the spread of tuberculosis (*Mycobacterium tuberculosis*) through infected sputum, and of plague (*Pasteurella pestis*), tularemia (*Pasteurella tularensis*), yaws (*Spirochaeta pertenue*), and trachoma.

Life History. The female lays one or more batches of eggs, some 100 to 150 in number, preferably on manure but also on other refuse or decaying matter. These hatch in 12 to 36 hours in warm weather. There are three larval instars which require a total of 4 to

6 days for complete development under favorable conditions. When fully developed, the larva or *maggot* crawls to a drier place, often under or at one side of the manure pile, and pupates. It overwinters in this form in colder climates, but in warm climates the adult emerges at the end of 3 or 4 days, mates, feeds, and begins to lay eggs. A complete cycle may require as little as 10 days or 2 weeks under optimum conditions of temperature.

CONTROL. Housefly control includes both individual and community measures. About the home, screening, trapping and the use of flypaper, fly sprays, and poison are all effective. A satisfactory and safe fly poison can be prepared as a 2 per cent solution of formalin in milk or sweetened water. Residual spraying with DDT applied at the rate of 200 milligrams per square foot, as described under malaria, is highly effective and lasting.

In rural areas especial care should be taken to prevent access to latrines or privies, by tight construction, screening and treatment with lime or oil. The principal breeding place on the farm, however, is the manure pile. Storage in screened bins, composting or frequent removal to the fields where it is thinly spread for rapid drying are recommended procedures. The *maggot trap* consists in a slatted false bottom under the manure pile. The full-grown maggots, in their search for a drier medium, crawl downward, through the openings and drop into a basin of water covered with a film of oil where they quickly perish.

Community measures are especially applicable to urban conditions. They can be summed up in one expression, *municipal housekeeping*. Efficient and regular garbage removal, with cooperation from the homes in the matter of cleanliness, is a primary requirement. General sanitation, including street cleaning, and regulation of abattoirs and other foci of decomposing organic matter, will go far toward reducing the fly population. It has been found especially important, in cities, to insist upon the frequent and thorough removal of horse manure (from the stables of milk distributors, for example). Various treatments have been proposed that will prevent fly breeding in manure, but better than any of these is clean storage in cement bins and removal at such frequent intervals, preferably weekly, as will surely interrupt the development of the larvae before they reach maturity.

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PART TWO

THE WATER CONTACT

Comparison with the Air Contact

Human contact with the environment by way of water may appear to be less intimate and less direct than by way of the air, but man, the biological mechanism, is as completely immersed in an aqueous medium as is the fish. His vital chemical reactions take place among reagents dissolved in water. His food becomes available for oxidation only after it has been made soluble and absorbable by digestion; and the oxygen necessary for its combustion is obtained from the air by solution in the body fluids within the lung tissue. These essential reagents are conveyed to the site of their actual use by the blood stream, which serves also to carry away the waste products.

It was not particularly noted, in the discussion of the air contact, that it is a two-way affair. Attention was directed chiefly to the incoming supply. If, perchance, the air became contaminated during use, replacement from the abundant available supply was the obvious remedy. Only in dealing with certain industrial pollutions were preventive measures considered. In brief, air pollution is temporary and local.

In the water contact we find a somewhat different situation. Cities bring in water from distances of hundreds of miles and may store it for a year or more. Thus, the water contact bridges time and distance. A typhoid fever case in the autumn, many miles away, so located and handled that the infectious dejecta may accumulate over the winter where they can be washed into the waterworks reservoir with the spring thaw, constitutes a definite health hazard.

Furthermore, man does not live, as if afloat upon a boundless ocean of usable water. His water supply is strictly limited. It flows in streams which provide many diverse and often incompatible services. In particular, the surface and ground water lakes and streams serve the dual purpose of domestic water supply and drainage, not only of single communities but often of scores of cities and towns as well, each in its turn using and polluting the waters.

THE CIRCULATORY WATER SYSTEM. In an organized community, the water supply system bears a striking resemblance to the circulatory blood system of the human body. A city requires a continuous stream of water delivered, perhaps by pumps, from a river or impounding reservoir. This incoming stream, like the arterial blood stream, is repeatedly subdivided within the municipal organism, finally reaching the place of its appointed service within the home or the factory. Here it reaches its final stage of subdivision in the plumbing which, like the capillary blood vessels, is both the site of use and the junction between the incoming and the outgoing streams. Within the plumbing system water becomes sewage* which, like the venous blood, carries off the waste products and is gathered

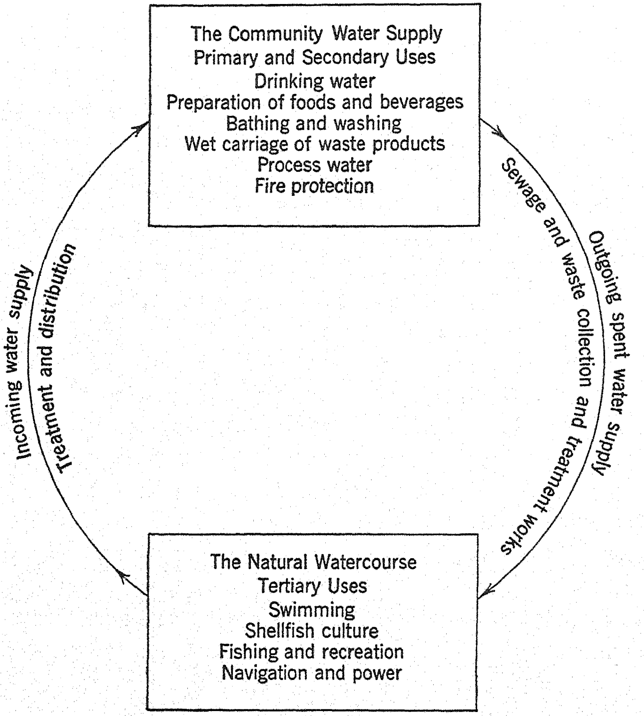

FIG. 40. The water-contact cycle.

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* One of the Spanish terms for sewage, *aquas usadas,* used waters, is most appropriate in this connection.

into continuously augmented streams—the house drain, the branch sewer, the trunk sewer—and finally returned to its source in a natural water course.

Thus, in addition to the great hydrologic cycle—evaporation, precipitation, stream runoff—there is a minor cycle involving man's use of water, water supply, sewage disposal, the stream. It is this cycle with which we shall have to deal in the chapters which follow. Because we deal with water as one of man's environmental contacts this cycle is called the water contact cycle.

THE THREE SEGMENTS OF THE WATER CONTACT CYCLE. In dealing with the water contact in the expanded sense in which it has been thus pictured, the cycle may well be treated as a whole. In the presentation of details, however, it is desirable to discuss the separate segments of the cycle under its three major categories: the incoming supply to the community (water supply), the outgoing spent water (sewage), and the natural watercourses (stream sanitation). Because of this convenient subdivision it is the more important to emphasize, at the outset, the essential continuity of the cycle and the integration of its parts (Figure 40). It is the water contact in its entirety which is vital to the community and of so great concern to the public health engineer. Failure to recognize the interrelationships of the parts leads to less than full utilization of water resources and, in many instances, to deliberate or unthinking abuse.

Water Uses and Abuses

THE USES OF WATER. Water use can be defined in three categories, paralleling, to an extent, the three segments of the water contact cycle just described.

Primary uses serve such strictly domestic purposes as drinking, preparation of foods and beverages, and bathing and washing. In the *secondary uses* water may be employed to carry off the waste products of the household or the factory; in industrial wet-processing operations; and for fire protection, street sprinkling, and the like. *Tertiary uses* include the use of water in natural watercourses for fishing, shellfish culture, bathing and recreation, navigation, power, and irrigation. The primary and secondary needs are supplied from a common system of engineering works requiring the diversion of water from its natural courses and its treatment and distribution throughout a network of pipes to the various users. The sewage and waste collection and treatment facilities are the corollary engineering works essential in the disposal of the outgoing spent water supply.

Our present interests center naturally about water supply for domestic use; but the objectives of public health engineering are so broad that our concepts of water use cannot be thus limited. In the development of any particular use consideration must be given to its relation and balance to other demands. The ideal in utilization of water resources is to obtain the maximum use consistent with reasonable conservation of that heritage. This requires an evaluation of all uses in each logical drainage basin and the mutual allocation of water among them. Such an ideal is not easily obtained, especially where many political and private interests are involved. Some groups are interested in using the watercourse for sewage disposal. Others need it for water supply. Still others may wish to divert the major portion of the dry weather flow, or they may be interested primarily in power, navigation, or recreation.

At first thought, it would appear that these divergent uses are mutually exclusive. Application of impartial engineering intelligence to the problem will show that multiple uses are not only possible, but also highly desirable, and, in the long run, provide maximum utility with the greatest benefit to all.

THE ABUSE OF WATER RESOURCES. Abuse of water resources consists of exploitation of a single use or a limited number of uses by local interests at the expense of use by others, or of impairment of future utility. Evidence of such abuses appears as

Upset of nature's balance in land–water–vegetative cover.
Excessive diversion of waters.
Excessive stream pollution.

UPSET OF NATURE'S BALANCE. The natural balance in land–water–vegetative cover may be disturbed by such operations as lumbering, misdirected agricultural activities, or large-scale drainage. It results in such permanent impairment of water and land resources as

Erosion and silting.
Increased runoff and flood intensity.
Lowering of dry weather flow.
Lowering of ground water tables and loss of well-water supplies.

EXCESSIVE DIVERSION. Excessive diversion of waters and lack of policy or of adequate machinery to deal with problems of mutual allocation of uses in comprehensive drainage areas have resulted in conflict between interests and have developed into court proceedings, where legal rather than engineering skill determines the outcome.

Stream Pollution. Excessive stream pollution is perhaps the greatest abuse of water resources. Up to 1934 and prior to the Federal aid construction programs of PWA (Public Works Administration) and WPA (Works Progress Administration), the situation in the continental United States, as regards the disposal of domestic sewage was approximately as follows:

	Millions
Total population (estimated 1934)	128
Urban	72
Rural	56
Population served by public water supply	80
By sanitary sewers	64
By sewage treatment plants	22
Population equivalent removed by treatment	6
Population equivalent discharged into waterways	58

In addition to this large volume of municipal sewage, quantities of strong industrial wastes are dumped into the rivers. Typical of these wastes are:

Suspended and colloidal mineral matter from coal and ore washing and other industries.

Dissolved mineral matter, acids and alkalies from metal industries.

Acid coal-mine drainage and salt waters from oil fields.

Oil and phenol wastes from oil refineries, gas and coke works.

Organic matter, vegetable and animal, from canneries, packing houses, tanneries, wool scouring, corn products, paper mills, milk products, etc.

Poisons of the heavy metals such as lead, arsenic, and cyanides.

The combined pollution load of municipal sewage and industrial wastes has resulted in the degeneration of many of our rivers to little more than open sewers, rendering the waters useless for all other purposes.

The development of multiple-purpose water-resource projects and of proper balances among the various uses is the responsibility of the public health engineer and necessarily broadens his thinking far beyond the limited concept of water intended simply as a potable water supply.

In brief summary, therefore, our studies of the control of the environmental water contact will deal with the stream as a whole; with its sources and the seasonal and geographical distribution of its runoff—the hydrologic cycle; with its manifold uses and abuses in the smaller circulatory system—the water contact cycle; with water quality in nature and as modified by man; with testing and standards of quality, with reference to intended use; and with the principles and practice of the treatment of polluted waters as employed in water purification and sewage treatment.

CHAPTER 9

HYDROLOGY

THE HYDROLOGIC CYCLE

Hydrology is defined as "the science which treats of the phenomena of water in all its states; of the distribution and occurrence of water in the earth's atmosphere, on the earth's surface, and in the soil and rock strata; and of the relation of these phenomena to the life and activities of man" (Meyer). Although recognizing the broad implication of this definition, we shall here deal only with limited aspects of the subject, related principally to quantity of surface and ground waters.

At a given time and place in nature's balance, a stabilization of environment is effected through a complex interrelationship of water, land, and vegetative cover. Stability of environment is relative, depending upon the time period. In terms of geologic time there are unmistakable signs of shifts, trends, cycles, or pulsations in stability of natural phenomena. However, the history of the world in the past 2000 years does not lead us to expect sudden changes in nature's balance. Although the long-time point of view is the guide to our philosophy of hydrology, the short historical period is the basis of engineering application.

Within the stabilized environment there is substantial variation in the interrelationship of water, land, and vegetative cover, and in the elements of vaporization, condensation, and precipitation, which, together, compose the hydrologic cycle. These variations differ in time and place and are defined by the laws of probability, rather than by fixed physical laws or definite periodicities.

The elements of the hydrologic cycle are traced in Figure 41 (from a report of the National Resources Board). The sun's energy vaporizes water through the processes of evaporation and transpiration. A portion of the rainfall is evaporated before it reaches the ground; a portion is intercepted by vegetation. Evaporation takes place from exposed water surfaces and from the moist soil. Large quantities of water also are vaporized through the phenomenon of *transpiration,* the breathing of the trees, shrubs, grasses, and cultivated crops.

Water vapor is lighter than air, and the warm moist air at the earth's surface tends to rise. Rising, it enters a more rarefied atmosphere and expands. Energy required for expansion is drawn from the air, resulting in cooling and condensation. Thus water which appears to be lost by evaporation cannot rise indefinitely into the atmosphere. Approximately 50 per cent of the total quantity of water vapor in the atmosphere is condensed before it ascends 1 mile above sea level; less than 10 per cent is found above 4 miles; all water vapor is trapped below a ceiling of 12 miles.

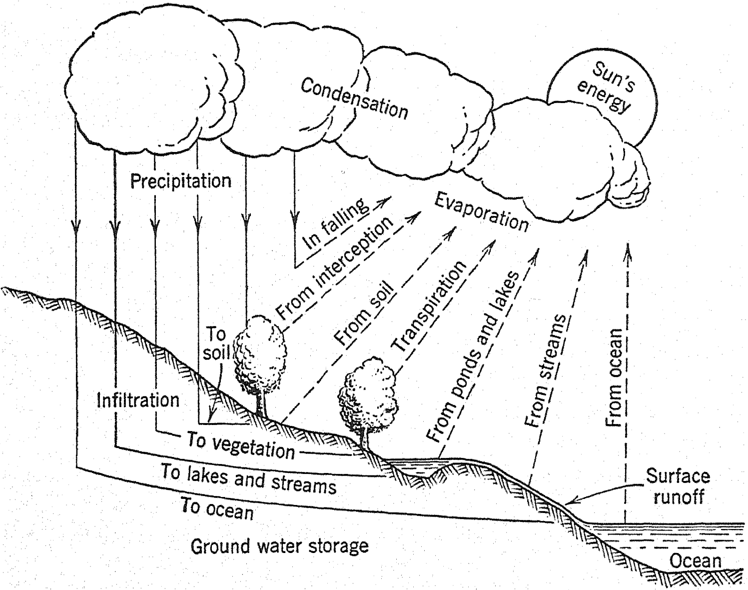

FIG. 41. The hydrologic cycle.

Unequal heating of the earth's surface induces convection currents and mass air movements which transport water vapor and condensed cloud formations over wide geographical areas. Precipitation, consequently, occurs unequally over different areas at irregular intervals.

Condensed vapor which falls as rain or snow upon the earth immediately divides into two streams. One of these makes a relatively rapid passage over the ground to the smaller tributaries, the main streams and, ultimately, to the ocean. The other makes a slower and more complex passage into and through the ground. It is absorbed by the spongy humus surface cover; some is retained in the upper soil, the remainder joins the vast body of ground water stored in the substrata. The ground water, in turn, moves slowly toward innumerable outcropping springs feeding into surface waters, ponds, lakes, and streams or directly to the ocean. It is this ground water seepage which principally maintains the river flows during dry periods and when precipitation occurs as snow.

A portion of the water retained in the soil goes to support vegetation and is transpired, and a portion is lost to land evaporation. Thus, the hydrologic cycle of vaporization, condensation, and precipitation is completed. In the great economy of nature water is neither lost nor gained. However, as we shall indicate later, man, through his activities can upset nature's balance of water, land, and vegetative cover, and greatly alter the local course of the cycle.

FACTORS AFFECTING RUNOFF

At any given point on a natural watercourse, there is an area above, defined by the topography, the precipitation upon which provides the stream flow at that point. This area which the stream drains is known as its *drainage area* or its *watershed*. The runoff from any drainage area is the total stream flow from that area over any given period of time. It may be estimated in terms of cubic feet or of gallons; it is commonly expressed in inches, it being understood that one inch represents the water that would cover the entire drainage area to that depth. It is also frequently expressed as a *yield,* that is, cubic feet per second per square mile of tributary drainage area. The yield is convenient for estimating runoff at various locations along the stream. Simply multiply the yield per square mile by the drainage area tributary to the respective locations. Where several yield values are available from subdrainage areas, a weighted yield in proportion to the size of these areas can be used for estimating the combined flow at downstream locations.

Runoff is compounded of three terms: precipitation, transpiration and evaporative losses, and ground water storage. In any long-term balance the amount of water stored in the ground will be substantially constant, and the runoff is simply precipitation minus losses. However, ground water storage, as indicated by the varying level of the water table, rises and falls from month to month through the seasons, following somewhat the precipitation pattern; and even as between the years there are low and high ground-water levels in years of drought or of heavy rainfall. We may write, therefore,

$$R = P - L - S$$

or runoff equals precipitation minus losses minus storage; storage being positive when the ground water has increased and negative when it has decreased. Thus, if the rainfall for the year has been 40 inches, and the transpiration and evaporation 20 inches, and, if there has been an increase in ground water storage equivalent to 2 inches, the net runoff will amount to 18 inches. The measurement of the ground water storage and the determination of that term in the runoff formula require an intimate knowledge of the drainage area and involve intricate hydrologic analysis, procedures for which however have been developed (Meyer).

PRECIPITATION

Precipitation patterns vary with geographical location, and, whereas average conditions define these patterns, wide departures from the averages are met in each location. The report of the Water Planning Committee, National Resources Board, shows annual precipitation throughout the United States.

In the Pacific Northwest, extremely high values (75 to 125 inches) are the result of *orographic precipitation*. Moisture-laden air from the ocean, forced upward in passing over the mountains, is expanded and cooled, and precipitation occurs on the windward side. On the leeward side, the air masses, freed of most of their moisture, again descend and are compressed and heated. In these arid regions rainfall may be as low as 5 inches per annum.

In other regions, *cyclonic precipitation,* associated with the translation of high- and low-pressure masses, is typical. This is responsible for the precipitation in the central and eastern areas which amounts to 50 or 60 inches in the Appalachians and 40 to 45 inches along the coast. There are wide variations, from year to year, from the long-term mean values. In addition to the annual variation, there are seasonal patterns peculiar to different geographical regions. In the winter cold air masses out of the Northwest move down the Misisissippi Valley and, gradually warmed in their southward passage, increase in moisture-holding capacity and, therefore, do not release rainfall. On the other hand, during the summer warm moisture-laden air moves out of the Gulf, up the Mississippi Valley, where it is cooled and provides rainfall during the active growing season. This is largely responsible for the Mississippi Basin's serving as the "breadbasket" for the world. It is indeed providential that no mountain range, such as flanks the Pacific Northwest, is located along the Gulf. In place of the great Mississippi we would then have an arid barren land.

Precipitation along the West Coast is high during the winter months and low during the summer. In the North Atlantic region there is practically uniform precipitation throughout the year, with but slight seasonal variation. Other regions show other characteristic seasonal distributions.

Storm rainfall, precipitation over short intervals of time, usually takes on a "haystack" form, high at the center and sloping off toward the periphery. It may be high and steep over small areas or flat and broad over more extensive areas. Great quantities of precipitation cannot occur over large areas; therefore, as the area of storm pattern increases, the average depth over the entire area decreases. Similarly, high intensities of rainfall (quantity per unit time interval) can occur only for short periods, and, as the duration of a storm lengthens, average intensity of rainfall diminishes.

In addition to variation with size of drainage area and duration of storm, precipitation varies in intensity almost with each occurrence, the intense storms occurring rarely, the moderate storms frequently. The frequency of occurrence at any location for any duration is determined by the laws of chance, which can be evaluated by statistical methods. It is this type of analysis for each particular region that forms the basis for practical engineering design for stream control and for community storm water drainage systems.

EVAPORATION AND TRANSPIRATION

The phenomenon of *evaporation* has been discussed under the Air Contact (p. 68). Temperature, relative humidity, and wind velocity are involved in evaporation from both water and land areas. Evaporation from water areas varies widely in different geographical regions, ranging from 20 inches per year for the cool damp Northeastern United States to as high as 90 inches per year in the hot dry Imperial Valley. Evaporation from land areas will generally range from one-third to one-half that from equal areas of exposed water surface. Precise methods for determining the loss through evaporation from natural or artificial water areas are available,* and Meyer gives reasonably accurate procedures for approximating the more complicated evaporation losses from land areas.

Transpiration is predominantly a function of the type of vegetative cover and is influenced by temperature and light. Vegetation does not transpire without sunlight, and transpiration is stimulated by a rise in temperature and ceases at the temperature of the dormant state. Transpiration losses, therefore, show a distinctly seasonal pattern. The normal transpiration over the active growing season for various types of vegetative cover is indicated in the following table:

	Inches
Grain and grass crops	9 to 10
Deciduous trees	8 to 12
Small brush	6 to 8
Coniferous trees	4 to 6

VARIATION IN RUNOFF

Since both precipitation and evaporative losses vary seasonally and geographically, corresponding variations in runoff are to be expected.

The *geographic pattern* of runoff in the United States, in terms of average annual yield is about as follows:

It is high in the Pacific Northwest, the larger streams yielding 75 inches per year, with some small tributaries as high as 125 inches. In the arid regions on the leeward side of the mountains the annual yield is very low, with a minimum of less than 1 inch per year. Many of the streams disappear entirely in the summer, and the shores of lakes recede, owing to excess of evaporation over runoff. Water supply in these areas, must be obtained from ground water sources, which, unfortunately, are also meager. Our water heritage in these regions is acutely appreciated by virtue of its scarcity.

From the fringe of the arid regions the annual yield of streams gradually increases to about 10 inches along the axis of the Mississippi, and then, proceeding eastward to the high ground of the

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* A. F. Meyer, Minnesota Resources Committee, St. Paul, Minn., June 1942.

Appalachians, runoff increases to 40 or 45 inches. It again diminishes down the eastern slopes toward the ocean to about 20 inches in the North Atlantic area and about 10 inches to the north and south.

The *seasonal distribution* of flow also varies widely, but, owing to high losses from evaporation and transpiration during warm weather, it does not parallel the seasonal rainfall pattern. With the exception of the Far West and Pacific Coast regions, low runoff occurs during the warm summer period or early fall. High runoff occurs during the winter and in the northern regions in the spring, when rainfall coincides with the melting of accumulated winter snows.

The pattern of seasonal variation is important in determining the quantity of regulated storage required to provide a sustained yield for water supply diversion or for maintaining sufficient runoff to avoid serious effects of pollution during drought periods. The *monthly hydrograph* (monthly average runoff plotted against time) affords a useful graphical representation of the seasonal pattern of flow (Figure 42).

The *daily variation* in runoff characterizes the *flashiness* or the *stability* of stream flow. It is determined principally by the characteristics of the drainage area, its shape, topography, and, particularly, the natural storage available in upland lakes and ponds. Flat topography, with 10 to 15 per cent of the drainage area in lakes, favors a steady smooth daily runoff, with generally less severe drought and flood flows. The daily characteristics are important in the study of natural purification of streams and in evaluation and interpretation of quantity and quality of waters in natural watercourses. These are reflected by the daily hydrograph (Figure 43).

The *frequency of occurrence* of extremes of runoff, floods, and particularly droughts, in addition to the general geographical, seasonal, and daily patterns of runoff, have a direct bearing on all segments of the water contact cycle, water supply, sewage disposal and tertiary uses of natural watercourses. The nature of the distribution of minimum flows and the determination of the frequency of any particular drought severity can be developed from a statistical analysis of the observed runoff over the years of record. Since drought flows form a series of minimum data, the distribution will be skewed from the "normal." An excellent means of determining the probabilities of such skewed data is afforded in an application of Gumbel's* method of analysis of the similarly skewed maximum data of flood flows.

As an example, Figure 44 shows a typical distribution of drought flows, based upon minimum monthly average river discharges, over a period of 45 years. (Only values below the mode are plotted, to which a line of best fit is applied.) Drought flows ranged from the least severe, 1930 cubic feet per second, to the most severe, 328 cubic feet per second, with a most probable minimum monthly average flow of 977 cubic feet per second. From this distribution is obtained the probability, or return period, of a drought of any severity. For example, a flow as low as 692 cubic feet per second is likely to return

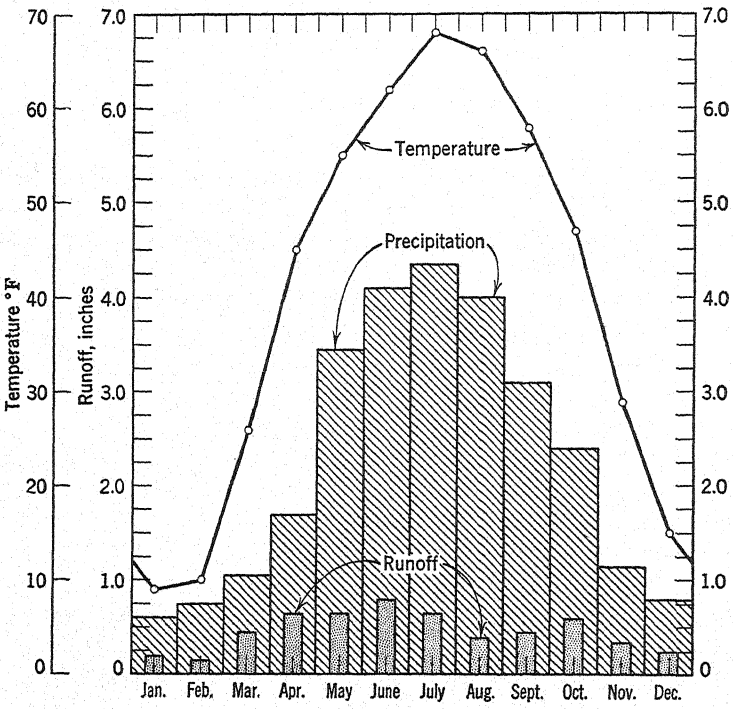

FIG. 42. Monthly hydrograph.

Typical of upper Mississippi River basin showing monthly mean runoff, temperature, and precipitation.

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* E. J. Gumbel, *Ann. Math. Statistics,* 12, no. 2, June 1941.

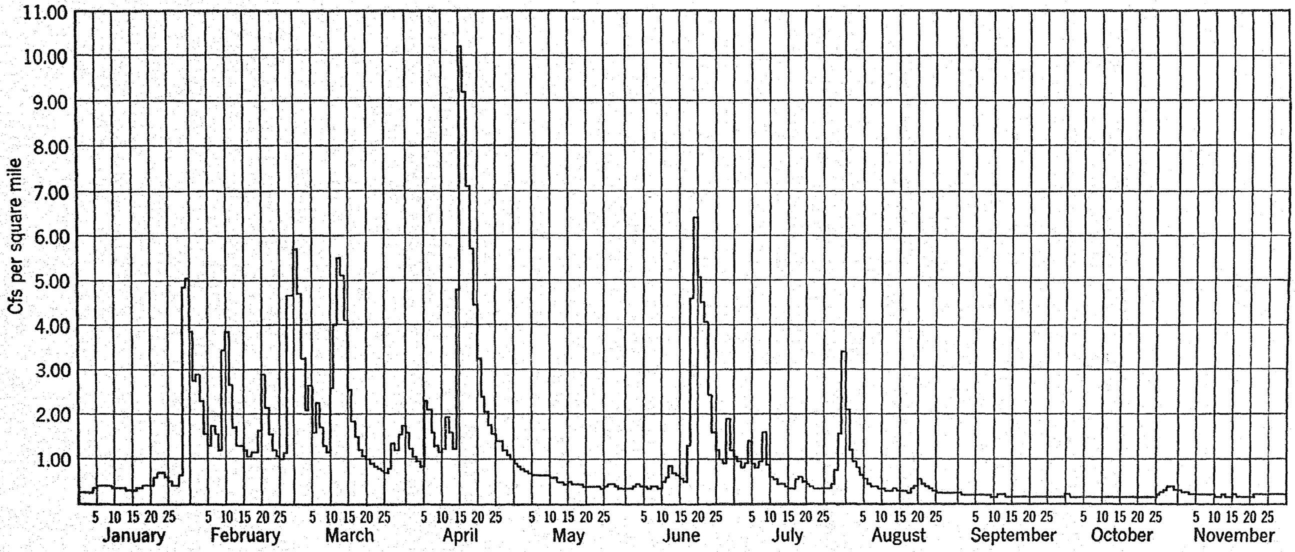
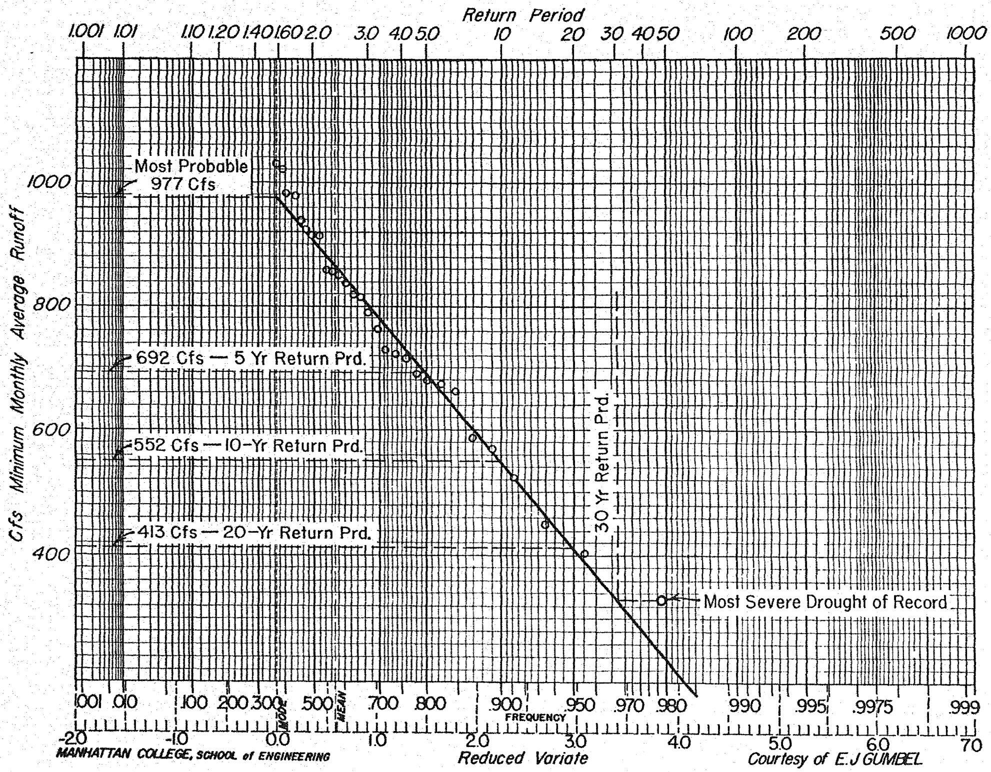


Fig. 43. Typical daily hydrograph, Miami River at Hamilton, 1939.



MANHATTAN COLLEGE, SCHOOL of ENGINEERING

Courtesy of E. J GUMBEL

FIG. 44. Distribution of drought flows, 45-year record, minimum monthly average runoff. Only drought flows below the mode are shown.

once in 5 years; one of 552 cubic feet per second once in 10 years; and one of 413 cubic feet per second once in 20 years. The most severe drought of record (328 cubic feet per second) has a most probable return period of 30 years.

STREAM FLOW RECORDS. The need for accurate continuous records of stream flow has led to the establishment by the U. S. Geological Survey of numerous *stream gaging stations* throughout the major river systems of the country. These stations actually record gage heights, or river stages, which are converted into corresponding runoff from a *rating curve* for the particular stations.

Records of observed runoff are available in the publications, "Surface Waters of the United States," *U. S. Geological Survey, Water Supply Papers*. These records constitute the basic data for all stream studies, power development, and flood control, as well as stream sanitation. Where records are meager or not available, they must be supplemented by the application of hydrologic principles in estimating precipitation minus losses (p. 262).

EROSION AND SILT POLLUTION

Erosion except in the slow geologic sense is evidence of an upset in nature's balance of water, land, and vegetative cover in the hydrologic cycle. It has its implications in the water contact cycle in the form of silt pollution. Erosion and its inevitable corollary, silt pollution, in some respects, constitute a much more difficult problem than sewage disposal. Proper sewage disposal can be provided at reasonable costs within a reasonable period of time by the construction of adequate treatment works, but repair of erosion and elimination of silt pollution may take generations. In the meantime, the quality of water deteriorates, fish life is destroyed, reservoir storage capacity is diminished by silt deposit, navigable channels must be frequently dredged, treatment of water supply is complicated, and every conceivable river use is impaired.

Erosion may be classified into three general types:

Sheet erosion, a uniform loss of top soil by wind and rain, scarcely recognizable.

Rill or shoestring erosion, small channels from water erosion, apparent following advanced sheet erosion.

Severe gully erosion, the deep jagged channels set up by heavy surface drainage from a series of shoestring channels.

The last two types are primarily responsible for heavy silt pollution.

Regulation and control of erosion is predominantly an agricultural engineering problem, involving intelligent agricultural practices, contour plowing, strip cropping, and winter coverage; the returning of steep areas to forest and pasture coverage; the control of grazing on the arid grass lands; more intelligent forest practice, selective cutting for lumber, reforestation, and forest fire prevention; check dams for incipient gullying; improved drainage practice in highway construction; headwaters control and upland flood protection.

GROUND WATER HYDROLOGY

TERMINOLOGY

Despite the efforts of various authorities to simplify it, the discussion of ground water problems is complicated by an unsatisfactory and varied terminology. Following Meinzer,* and (later) Tolman,† we use the term *subsurface water* to apply to all waters beneath the surface of the ground, and the term *underground* and its Latin equivalent, *subterranean,* is avoided.

Waters lying within the ground are divided into two zones, the zone of aeration and the zone of saturation, according to the manner in which they are held in the soil or rock. Some of the water, upon entering the ground, is drawn by gravity into a layer which saturates the soil and is under hydrostatic pressure. The upper surface of this layer would be defined by the water level in a well. This surface is the *water table*. It separates the *zone of saturation* from the *zone of aeration*. The water within the zone of saturation is the *ground water,* (*phreatic water* of Meinzer), from the Greek *phreatos,* well.

The water in the zone of aeration (above the water table), is *suspended water*. It is of several kinds, depending upon its reaction to the force of gravity. Immediately above the water table lies the *capillary fringe*. Here the water is held by capillary forces. This water may or may not saturate the soil, its depth and the degree of saturation depending upon the size of the openings. Being in equilibrium between gravity and the capillary forces, it will not run out into a well.

Above the capillary fringe lies the *gravity* or *vadose water,* (Latin, *vadosus,* shallow). It is in movement toward the water table under

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* O. E. Meinzer, *U. S. Geol. Survey Water Supply Paper* 494, 1923.

† C. F. Tolman, *Ground Water,* McGraw-Hill, New York, 1937.

gravity and against the resistance of the soil. Above this, Tolman distinguishes the *pellicular water* (Latin, *pellicula,* a thin skin or membrane), adhering as a skin to the soil particles and held there against the pull of gravity by molecular adhesion. It may move upward to replace water lost by evaporation or transpiration in the layer above. The uppermost layer carries the *soil water,* available to plant roots and continuously lost by land evaporation or by transpiration through plant foliage.

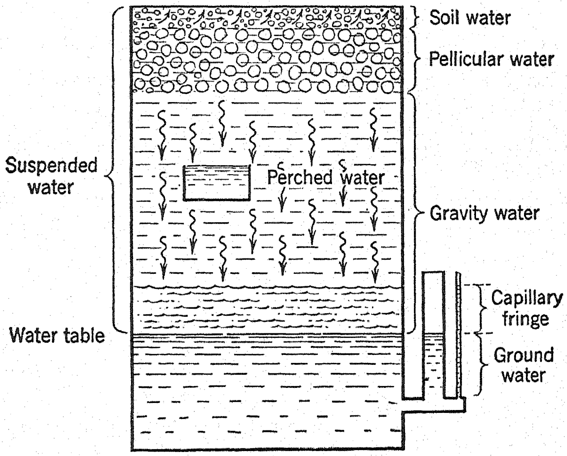

FIG. 45. Laboratory model of ground-water conditions.

If within this system there is any basin-like depression in an impervious stratum, such as clay, there may be a false water table at the elevation of the overflow rim of this structure. Such water is known as *perched water.*

A LABORATORY MODEL

These various zones and waters are indicated in Figure 45, as they might appear in a glass jar in the laboratory. The jar is filled with sand. Water has been added at the surface some time previously. At the moment we see the moist sand near the surface; some of this moisture is moving upward to replace evaporation. Next comes the stratum of gravity water moving downward. At the bottom the layer of saturated sand contains water under pressure, as indicated by the fact that it rises in the side outlet to the height of the water table. A small capillary tube is also indicated, representative of the size of pore openings among the sand grains. In such a tube the water will rise above the water table, illustrating the capillary fringe. Finally, a cup has been placed in the sand. It fills to the rim and illustrates perched water.

Note that these conditions are temporary. Immediately after the "rain," the upper layer was saturated with gravity water. This moved downward, leaving the soil and pellicular water. Eventually, it will all drain through the capillary fringe and into the ground water. Thus the gravity water may at times occupy any part, or all of the zone of aeration, and final equilibrium conditions will find it in the ground water; the water of the capillary fringe is draining to the ground water as fast as it is replaced by gravity water from above; the soil and pellicular waters are subject to continuous loss by evaporation and transpiration, and are replenished by rainfall or irrigation.

The sand in the jar represents a water-bearing geological stratum or *aquifer*. In any given locality, there may be several aquifers superimposed on one another and separated by relatively impervious strata, so that there is little or no commingling of the waters. Only the uppermost of these has a free water table, that is, one exposed to the air, through the overlying ground and receiving the immediate drainage of the overlying surface. The others represent *confined waters*. They are supplied from more remote areas where the aquifer in which they reside outcrops at the surface. This area is the *intake* or *recharge area*. Confined waters may be under sufficient pressure to bring them to the ground surface or above it, in which case they are generally known as *artesian waters*.

THE MOVEMENT OF GROUND WATER

The movements thus far discussed have been vertical movements; the ground water has been regarded as an underground lake with its surface at the water table. But even lake surfaces slope slightly toward the outlet end if there is any horizontal flow.

The slope of such a free surface is the *hydraulic gradient*. If small, it is generally expressed in inches or feet per mile or per thousand feet. If large, it may be expressed in per cent or vertical feet per hundred feet of linear distance. The gradients of slowly moving ground waters vary directly as the velocity, and inversely with a upon the proportion of open space, *porosity,* and size of pore openings. These gradients represent the slopes of the water table surface, that is, free surfaces under atmospheric pressure (through the soil), and comparable with open lake surfaces. Confined ground waters simulate water flowing under pressure in pipes. Contrary to the maxim such waters will *flow uphill.* The true gradient may be determined by the difference between the free surface levels in two wells, entering the aquifer at points some distance apart.

Free ground waters, then, have surface gradients that are related to the velocity of their free movements under gravity. They have no pressures above the water table level. *Confined* ground waters may be under hydraulic pressures, determined by a free surface at some other place, at times remote, and in the direction of the outcrop of the particular aquifer which contains them.

GROUND WATER STABILITY AND DEPLETION

Within nature's balance of land, water, and vegetative cover, ground water stability is achieved in each geographical area. In undisturbed nature, seasonal and yearly fluctuations in ground water tend to balance about a constant level. In humid areas where precipitation is high, ground water is generally abundant with a shallow stable water table. In arid regions, conversely, ground water is scarce, with a deep water table subject to wider amplitudes in variation above and below the normal level.

Within any particular climatological pattern ground water availability, in turn, will be dependent upon the character of the *soil,* the nature of the *vegetative cover,* and the *topography.* Pervious soil formations overlain with organic humus top soil maintained and protected by vegetative cover yield abundant ground water. Impervious clay and rock formations and barren areas devoid of natural humus do not permit absorption and infiltration and, hence, yield little or no ground water. The flat low valley areas are the natural intakes of aquifers, while the steep slopes favor surface runoff.

The impact of man's activities on nature's balance of ground water is evidenced by the progressive lowering of water table levels observed over the past quarter century, particularly in the arid regions of the Mississippi River Basin, the Middle West, and the Northwest (Table 33).*

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* Report of the Mississippi Valley Committee of the Public Works Administration, Washington, D. C., 1934.

TABLE 33

Observed Lowering of Water Table Levels

(After Mississippi Valley Commission)

	Feet
South Dakota	10 to 35 (some areas as much as 70)
North Dakota	10 to 30
Nebraska	10 to 20 (some areas as much as 30)
Minnesota	10 to 20
Iowa	10 (fairly uniform over the state)
Missouri and Kansas	Less than 10

Further evidence of depletion of ground water in arid regions is the progressive recession of lake areas, the drying up of springs, and the diminution of stream flow during the dry weather seasons. The causes of this upset in nature's balance are man-made, predominantly associated with destruction of vegetative cover and subsequent erosion of absorptive humus top soil, resulting from improper agricultural practices; excessive lumbering and overgrazing; and excessive artificial drainage, for agricultural purposes, of low valley areas and natural swamplands. These trends in ground-water depletion seriously threaten ground-water supplies and aggravate stream sanitation problems associated with low stream flow.

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CHAPTER 10

WATER QUALITY

THE EVALUATION OF QUALITY

For the purpose of technical and administrative control of the water contact in any segment of the cycle, it has been necessary to adopt certain standard examinations and procedures for the measurement and definition of quality.

Certain of these procedures are uniquely associated with the determination of certain phases of water quality in one or another segment. The same *classes* of examinations, however, apply throughout the cycle; in fact, in studying the incoming segment, water supply, it is quite necessary to make examinations around the entire cycle in order to evaluate quality properly for primary community uses.

Classifications of Examinations and Procedures. These examinations may conveniently be considered in the following five classes:

1. *Bacteriological* examinations to indicate indirectly the presence of pathogenic organisms or any impending threat of their presence.
2. *Chemical* analyses for the quantitative determination of any poisonous, injurious, or deleterious chemical constituent, organic or inorganic.
3. *Physical* examinations to indicate and measure certain physical properties or conditions.
4. *Microscopic* examinations for the identification and quantitative enumeration of objectionable taste- and odor-producing microscopic plants and animals, the so-called micro-organisms.
5. The *Sanitary Field Survey,* for the purpose of providing a physical picture of the entire water cycle in relation to potential sources of pollution.

It is only from the composite evaluation of all five major examinations, rather than upon the basis of any one specific procedure or test, that the quality of water for primary uses can be judged.

The quality of water, dependent as it is upon concentrations of both animate and inanimate impurities, is never static; it is subject to constant change. Consequently, the results of examinations give but an instantaneous cross-sectional picture of conditions as of the time of sampling. Moreover, the samples taken for testing are but very small portions of the quantities actually used; they may not always be truly representative. Samples should, therefore, be sufficient in number and taken with sufficient frequency to assure a fair evaluation of the trend of quality and its variations.

The detailed tests and techniques are fully described in *Standard Methods*. In what follows it is sufficient to deal only with their significance. The examinations yield only factual data. Beyond their mere collection and tabulation, these data require suitable interpretation and evaluation. The scientific skills necessary to collect reliable data can readily be acquired, but the judgment essential for interpretation calls for basic understanding of the relation of water characteristics to respective uses.

RELATIVE PURITY IN RELATION TO INTENDED USE. For general municipal purposes, street cleaning, fire fighting, or lawn sprinkling, the quality of water is not of particular interest. For various industrial uses waters of definite specifications as to chemical purity and physical characteristics are frequently demanded. Lakes and streams have their own specific quality requirements related to use. Water supply for domestic use, the highest ranking use of water, calls for still other specifications of quality. These have to do primarily with hygienic quality, although to a certain extent it is necessary to consider aesthetic quality as well.

The expression *pure and wholesome water* has become conventional as a descriptive term for a satisfactory domestic supply. This expression seems to connote a certain rather definite thing. When, however, as frequently happens, it is desired to provide a legal definition or to give more detailed consideration to the minimum requirements which will satisfy this more general specification, it becomes necessary to expand its meaning much more fully and definitely.

We may grant at the outset that purity is emblematic rather than a specific characterization. No waters in nature are pure in the chemical sense. Furthermore, impurities have a relative significance determined wholly by their individual characteristics, in relation to the specific use to which the water is to be put. The salts of calcium and magnesium, for example, constituting hardness in water, are highly objectionable for certain industrial processes such as for a steam boiler operation. Typhoid fever germs in this particular use have very little significance. For domestic use hardness is only a moderately objectionable characteristic, whereas pathogenic organisms represent the extreme of dangerous pollution.

Moreover, even undesirable impurities may be accepted, within specified limits of tolerance, as a matter of expediency. The very stringent standards of purity set up in the standards of the U. S. Public Health Service permit a limited concentration of the sewage organism, *E. coli,* in frank recognition of the fact that purity and safety are relative values and that perfection is unattainable.

Relative purity as applied to the conditions of practice, therefore, deals (1) with the use to which the water is to be put and (2) with permissible limits of impurity with respect to that use and with respect also to the feasibility and cost of obtaining a less impure water. With these facts in mind, we may define a pure water for domestic purposes as *a water which contains no harmful or deleterious substances with respect to human physiology,* and then consider the degree of departure from this ideal which may properly be accepted.

This definition embraces two distinct types of impurity. The limitation first is to harmfulness and refers to such toxic substances as lead, to substances physiologically harmful such as excessive concentrations of magnesium and to any material evidence of pollution by human excreta. Deleterious substances merely detract from the value of the water; they make it less attractive to the consumer and thus tend to limit its use or invite the substitution of bottled or other waters, often of less desirable hygienic quality. Examples of this class of impurities are such harmless substances as suspended clay and natural organic color and many of the tastes and odors in water that result from the growth of microscopic plant and animal life.

SPECIFICATIONS AND TOLERANCES. Precise engineering specifications usually set up a desired result and require compliance within certain limits, known as tolerance. Thus a specification for a shaft or a gear as part of a machine of precision may call for an exact dimension, plus or minus a very small variation. In a less precise mechanism the same dimension may be associated with a greater tolerance, in recognition of the fact that it is more difficult and expensive to secure the closer fit. The tolerance is determined by the requirements of the job in comparison with the cost of additional refinement.

The word tolerance is a fortunate one in connection with public health codes and standards in general. It suggests physiological and aesthetic limitations: the amount of an impurity or the extent of departure from the optimum which will be tolerated by the individual without impairment of health or offence to the senses.

THE PRINCIPLE OF EXPEDIENCY

We also recognize here the important principle that tolerances are a concession to expediency, that the optimum or ideal condition is seldom obtainable in practice, and that it is wasteful and therefore inexpedient to require a nearer approach to it than is readily obtainable under current engineering practices and at justifiable costs.

For example, the specification, *no evidence of sewage pollution,* an ideal condition, can seldom be met by the employment of the customary water treatment processes. In 1900 the old slow-sand filter at Lawrence, Mass., treating the highly polluted water of the Merrimac River, had been in operation for several years, and its installation had been followed by an immediate and spectacular drop in the typhoid fever death rate of the city. This filter represented the best engineering knowledge of its day, and it was operated under careful supervision and bacteriological control by the scientists of the Lawrence Experiment Station of the Massachusetts State Board of Health. On the basis of filter performance and epidemiological evidence, the standard of acceptable performance adopted at that time was, *not over 50 per cent of the one milliliter samples examined to be positive for B. coli, the characteristic sewage organism*. This was equivalent to a permissible concentration of 69 organisms per 100 milliliters.

When the U. S. Public Health Service in 1910 promulgated its first standards for water quality, it was entirely feasible to call for not more than two bacteria of the coliform type per 100 milliliters of water. There had been many improvements in the general practice of water treatment in the interim, but the greatest change that had taken place had been the introduction of chlorination, a process so simple, so economical, and so effective that without operational or financial hardships the more stringent specifications could readily be met.

Administrative standards must be sufficiently precise for legal enforcement. Like the speed laws for the control of traffic, they must set up an arbitrary line between good and bad, the permissible and the forbidden, where no such line has any real meaning or specific justification. This situation is unfortunate but unavoidable.

The late William Thompson Sedgwick, a pioneer in public health, taught his classes that "standards are devices to keep the lazy mind from thinking." It will be well for the public health engineer, in the interests of his own clear thinking, to examine the data and the reasoning which underlie our present-day standards, codes, and rules, as they apply to commodities and to the physical environment in general. One who is to enforce these provisions should have a much better understanding of their true merit than is implied in the printed documents.

SAFETY. One principal aim of standards is to provide protection; to establish a safe environment. Yet safety itself is merely relative, for perfect safety is, again, an ideal. In whatever direction we pursue our studies we shall find always a certain limit beyond which it has not thus far been possible to go in the direction of complete protection. Protective devices yield always a percentage improvement; so that successive applications of remedial treatments merely multiply percentages of over-all benefits.

Thus not only do such devices fall short of perfection in practice, but, by their very nature, ultimate perfection is theoretically impossible. It is well, therefore, in our thinking at least, to abandon such concepts as *a safe water* or *a safe milk* and to substitute some numerical or at least some relative idea. Of two supplies, each passing an established administrative standard of quality, that one is surely the safer which passes by the wider margin, if the standard itself is any true measure of relative safety.

CRITERIA OF RELATIVE SAFETY. Upon what basis then are standards of bacterial quality in a public water supply to be justified? Epidemiological data are, of course, of major value. Water-borne epidemics of typhoid fever were at one time a common experience. They were markedly reduced or totally eliminated by a limited degree of water purification. Any minor incidence of the disease, due to residual water pollution, became submerged below the general level of incidence from all causes. At this level the statistics of water-borne disease failed to provide a scientific criterion for a standard of permissible residual pollution.

But a proper appreciation of the basic fact that safety is relative and that water purification also yields only relative improvement justifies us now in applying the much more stringent standard that has become feasible, and thus expedient, with the practice of chlorination. By the same reasoning, if we would be quite honest, we will recognize that the higher standards provide us with a *safer* water but not necessarily a *safe* water. Pollution of sewage origin is potentially a source of typhoid fever, regardless of the absence of traceable outbreaks of the disease. All subsequent improvement is relative—a certain per cent. Under the same conditions of purification, a greater initial dosage yields a greater final product, and any initial dosage greater than zero yields some final product.

This philosophy has been well expressed in the following summary of an excellent discussion of the whole matter:

> While there is no widespread typhoid fever due to water supplies which meet present standards, as proved by present low typhoid rates, there is equally no assurance that an occasional case of water-borne typhoid fever does not develop under such conditions.*

A broader application and appreciation of this logic would greatly clarify our thinking and simplify our practice in many of the diverse fields of public health.

HEALTH HAZARDS. There are other aspects of this matter and other criteria not expressible in numerical terms. A competent fire department inspector will order the removal of a mass of boxes and paper from the rear room of a store on the ground that it constitutes a fire hazard. He has no interest in the admitted fact that no fire has occurred there. The conditions are obviously such as to provide a fire if a cigarette or match be carelessly thrown away.

Similarly, a health hazard may be defined as a condition which, judged on the basis of knowledge and experience, may, under certain contingencies, ignite and produce an epidemic. There may be no epidemiological data uniquely applicable to this case. Nothing has as yet come of it. By what criteria then is this situation judged? Merely upon general knowledge and experience.

A privy draining into a water supply provides a good example. Accepted scientific facts show that, given the added condition of a typhoid fever case on the premises, the typhoid bacteria could live a long time in the excreta; could, if washed into the stream, survive the passage to the waterworks; and might survive, in some measure, the

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* R. W. Kehr and C. T. Butterfield, *U. S. Pub. Health Service, Pub. Health Repts.*, **58**, 589, 1943.

purification treatment. This is general knowledge applicable to any specific situation. It is no defense to point out that the contingency of a typhoid fever case is lacking.

Experience may be regarded as a sort of statistical epidemiology. It teaches that in the past and under similar conditions harm has resulted. Thus laboratory science concerning the possibility of disease transmission is confirmed by experience of its reality. Whereas not demonstrably harmful at the moment, the situation presents a health hazard with an associated probability.

Each of these situations, the one dealing with a definite numerical reduction of an existing and measurable danger, and the other, dealing with danger from a situation not yet developed, appears to yield a *probability* as a measure of relative safety. But administrative standards must define *limits;* limits, for example, of permissible concentrations of bacteria of fecal origin in a water. Since these limits merely separate the less safe from the more safe, how can such standards be defended? Why, for example, set up more severe standards for indoor swimming pools than for the public beaches?

EXPEDIENCY. The principle of expediency is generally the guiding principle in situations of this sort, although this fact is not always recognized, and less frequently admitted.

It is attempted to reduce the numerical measure of probable harm, or the logical measure of existing hazard, to the lowest level that is practicable and feasible within the limitations of financial resources and engineering skill. Progressive improvement is increasingly more expensive and a level is reached in every case where it is either impracticable from an engineering point of view, or excessively expensive to proceed.

On the score of expenditure, it is always necessary to regard the health budget as a whole. A well-planned program of health protection would not justify an additional large expenditure on watershed control, for example, even if it were thought that this would provide a little additional protection, if, at the same time, it were certain that the same sum expended on a tuberculosis hospital would eliminate much more sickness and save many more lives.

On the engineering side, the law of diminishing returns is always in evidence. The natural law of geometric decrease indicates that it is as easy to produce the first 90 per cent of improvement as the next 9. There are also natural limitations to engineering skill, although these are being continuously overcome by research and mechanical improvement.

Without chlorination, for example, the present high bacterial standards for potable water could be reached, if at all, only by means so expensive that they would never be justified by any existing epidemiological evidence. With chlorination, water of high quality is readily and economically obtained; and this fact justifies the high standards that are now almost universally applied.

The principle of expediency is the logical basis for administrative standards and should be frankly stated in their defense. It merely holds that it is desirable to achieve the maximum degree of protection which may be attained within reasonable financial and engineering limitations, and with regard to the relative needs and benefits of other public health measures. Just what are reasonable public health budgets and private expenditures for health protection may be a matter of education and of progress. The distribution of these budgets, however, should be made upon the very elementary basis of *the most for the dollar.*

THE IMPURITIES OF WATERS

The common impurities found in natural waters and acceptable, within limits, in waters for specified uses, may, for convenience, be classified as mineral (inorganic) and organic.

MINERAL IMPURITIES

SODIUM CHLORIDE. Sodium chloride or common salt is perhaps the most prevalent of all mineral impurities. It is an almost universal constituent of natural waters. Human consumption of salt, taken with food and physiologically essential, so far exceeds any normal intake by way of domestic water that no limitation need be placed upon this constituent of a potable water. Concentrations of over 20 parts of chloride per million may accelerate corrosion of pipes and fixtures. This concentration is rarely found in normal waters, except near the sea and in deep wells reaching into geological deposits of salt.

Before the development of bacteriological methods for the examination of water, the chloride concentration was regarded as an index of the extent of undesirable pollution. It is normally excreted by man at a fairly constant rate per capita, and is unaltered in the soil, through which it percolates. The *normal chlorine*[*] of the district was determined by the examination of normal unpolluted waters; it was found, after rather extensive study, to be related to the distance from the seacoast. Any excess over the normal for the district was regarded as of probable human or animal origin. In Massachusetts, a population of 100 persons per square mile was found to increase the chloride content of the ground water by about one-half part per million.

HARDNESS. The salts of calcium and magnesium, which together constitute the major part of the so-called hardness, are probably next in order of general prevalence and rank first in quantitative importance among the mineral impurities of natural waters. Here again within the ordinary limitations of palatability there is little hygienic significance. Suggestions that hard waters are definitely harmful in connection with certain pathological conditions of the joints must at best be interpreted in relation to the individual case and on the basis of a definite medical diagnosis. On the other hand, the suggestion has been advanced by one highly qualified in human nutrition[†] that under modern conditions, in which prepared foods play so important a role in our daily lives, there may be and often is a distinct deficiency in our daily calcium intake, which is partially compensated by a moderate calcium content in the domestic water supply.

Upper limits of permissible concentrations of both calcium and magnesium are based upon inconvenience and wastefulness due to the coagulation of soap and incrustation upon cooking utensils, rather than upon hygienic objection. The coagulated soap clings to the clothing and makes good clean laundering difficult or impossible. For this reason commercial launderies and all textile mill operations require a soft water. Hard waters also tend to clog the household plumbing by accumulation of the coagulated soap.

A total hardness of over 100 parts per million becomes increasingly unsatisfactory for these reasons, while lesser concentrations are generally accepted without complaint. It appears to be true also that consumers of hard water are often temporarily "upset" upon changing to a soft water, and *vice versa*. This probably is related to the

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[*] In the older texts the term chlorine implied *as chlorides,* that is, dissociated chloride ions. The more exact term, *chloride* or *chloride ion,* is the more desirable now in view of the use of chlorine itself in water treatment.

[†] Professor Henry C. Sherman of Columbia University.

physiological salt balance. The laxative effect of magnesium salts also makes it desirable to limit them to a concentration of not over 125 parts per million of magnesium.

From the point of view of industrial use and of water softening, it is convenient to distinguish between calcium bicarbonate and the other salts of calcium and magnesium. The former becomes unstable when the water is heated, releasing carbon dioxide and forming the insoluble calcium carbonate. Hardness due to calcium bicarbonate is therefore known as *temporary hardness* in distinction from permanent hardness due to other salts of calcium and all the magnesium compounds. These matters are discussed in more detail under water softening.

IRON AND MANGANESE. Iron occurs in many natural waters and in various chemical combinations. In ground waters, it is frequently found as ferrous bicarbonate, or possibly in a mixture of less definite chemical composition resulting from the solution of the insoluble ferrous hydroxide by carbonic acid. The oxidation of the mineral pyrite, FeS, forms ferrous sulphate which hydrolyzes in water to free sulphuric acid and ferrous hydroxide.

Iron is also a constituent of the chlorophyl of green leaves, and high concentrations of iron are found in swamp waters and in low-lying ponds with deficient drainage. This iron is in organic combination until worked over by bacteria during the decomposition of the leaves, when it becomes oxidized to the familiar red slime which characterizes such waters. In many places, extensive deposits of *bog iron ore* occur suitable for mining. These are the residues of the organic iron deposits.

In a water for domestic supply the objection to iron is primarily aesthetic. Not only does iron act like calcium as a hardness constituent, but also its precipitated soap is highly colored, and in some of its forms it precipitates spontaneously upon heating or exposure to the air, causing unsightly stains upon bathroom fixtures and cooking utensils. A limitation of 0.3 parts per million is generally placed upon iron in a drinking water.

Iron in the process water is most objectionable in certain industries, notably in the textile trades and in paper making.

Manganese is quite similar to iron in its occurrence and reactions. It, too, is a constituent of leaves, where it usually represents about 10 per cent of the total iron–manganese content. In some of the red-leaved trees, however, such as the swamp or scarlet oak, the author has found more manganese than iron.

ALKALINITY, ACIDITY AND *p*H. Somewhat closely associated with the hardness of a water are the various expressions which have to do with its alkalinity or acidity. An alkaline reaction in chemistry means one in which the influence of the negative or hydroxyl ion, OH^-, prevails, as contrasted with an acid reaction in which the opposing positive hydrogen ion, H^+, is in excess. Pure water itself dissociates very slightly according to the following relation:

$$H_2O = H^+ + OH^-$$

The products of such a dissociation each carry an electrostatic charge. The two charges, being equal and opposite, balance and maintain the initial neutrality of the water. Dilute solutions of hydrochloric acid and of sodium hydroxide are dissociated in a similar manner:

$$HCl = H^+ + Cl^-$$
$$NaOH = Na^+ + OH^-$$

Under any of these circumstances a simple law controls the equilibrium condition which determines the respective concentrations. The product of the concentrations of the hydrogen and the hydroxyl ions, taken in molar quantities per liter, is always equal to 10^{-14}. Therefore, in dissociated neutral water, the concentration of each of the two ions is 10^{-7}.

In a dilute hydrochloric acid solution, if the concentration of the hydrogen ion is 10^{-2}, or 1/100 normal, then the theoretical concentration of hydroxyl is 10^{-12}, or one million millionth normal; and similarly for an alkaline solution. Some acids, like acetic acid, and alkalies, like ammonia, dissociate only partially; these are known as weak acids or alkalies. Suitable chemical titration, however, develops the full measure of the concentration of these compounds, and records the acidity or alkalinity of the solution. These may be regarded as quantity measures; they indicate the quantity of acid or alkali required for neutralization.

The existing concentration of the *dissociation products,* on the other hand, represent the *intensity term.* It is this factor which is associated with corrosion and with the growth and activity of bacteria. It is the *effective reaction,* at present existing, regardless of the *latent reaction* which comes into play only when neutralization or some other form of utilization is attempted. This intensity of reaction is indicated by the *hydrogen ion concentration,* the actual concentration of the dissociated hydrogen ion. It could be stated for convenience, the exponent of 10 is taken with changed sign and given the symbol *p*H. The *p*H of the hundredth normal hydrochloric acid solution, if fully dissociated, is 2, and, of the millionth normal, 6. Thus the *p*H value is merely the negative logarithm or the logarithm of the reciprocal of the hydrogen-ion concentration. If the basic equilibrium between hydrogen and hydroxyl ions is recalled it may be seen that a *p*H of 6 represents a hydroxyl concentration of 10^{-8}, and a *p*H of 2, one of 10^{-12}. These might with equal propriety be represented by *p*OH 8 and 12, respectively, but this expression is unnecessary and not employed. The hydroxyl concentration is readily obtainable from the *p*H values.

The present Public Health Service standards specify that a water should not have a *p*H greater than 10.6, nor an alkalinity due to normal carbonate, that is, excluding any bicarbonate, in excess of 120 parts per million. A lower limit for *p*H, upper limit of acidity, is not set up, as it would have little hygienic significance; it would, in fact, prevent the dispensing of lemonade on common carriers. Acidity does become a feature of importance, however, in connection with the corrosive properties of a water; this is discussed in a later section.

FLUORINE. Fluorine, occuring as fluoride in the ground waters of a considerable portion of the United States, has been definitely recognized as the causative agency in *dental fluorosis,* or *mottled enamel,* a pathological condition of the teeth.* Only the teeth of young children are affected, and a child who begins to take fluorine before all his teeth have been formed will have mottling only on those teeth formed thereafter. In animal experimentation, higher dosages of fluorine produce a picture of rickets which can be compensated by an additional calcium intake. This is not true, however, with mottled enamel, nor does the addition of vitamin D to the diet improve the situation to any degree.

In addition to the possible intake of fluorine through the domestic water, attention has been directed to other sources, noticeably the use of fertilizer material containing fluoride on garden crops and of insect sprays.

More recently a striking inverse correlation has been observed between low concentrations of fluoride and dental caries.† These

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* Fluorine and Dental Health, *Pub. Am. Assoc. Advance. Sci.* No. **19**, 1942.

† H. T. Dean, F. A. Arnold, Jr., and E. Elvove, *U. S. Pub. Health Service, Pub. Health Repts.*, **57**, 1155, August 1942.

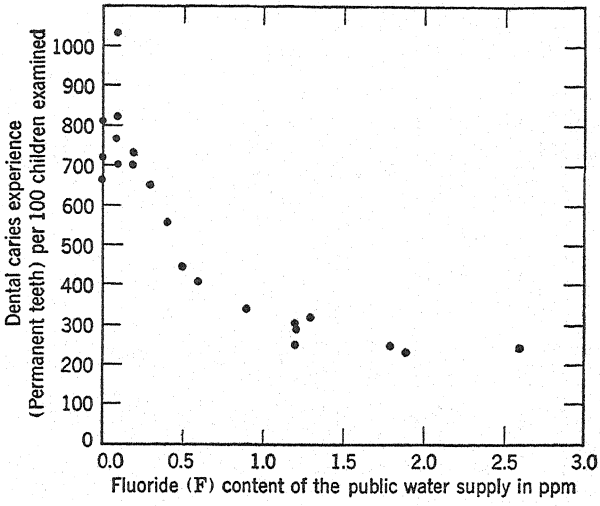

FIG. 46. Relation between the amount of dental caries (permanent teeth) observed in 7257 selected 12–14-year-old white school children of 21 cities of 4 states and the fluoride (F) content of public water supply. (H. T. Dean, F. A. Arnold, Jr., and E. Elvove. *Pub. Health Rept.* 57: 1155–1179, Aug. 7, 1942. Reproduced by permission of the authors.)

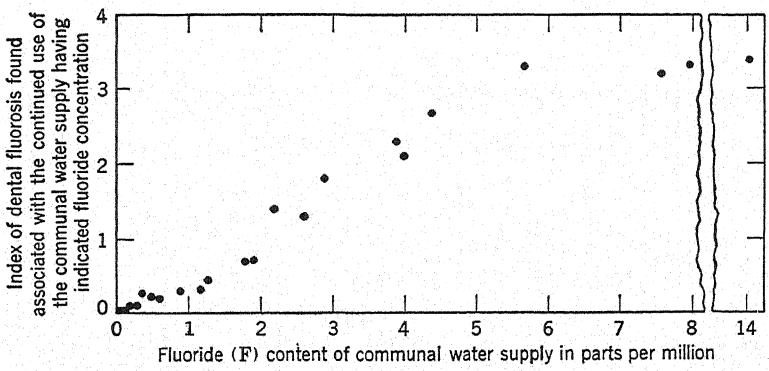

FIG. 47. Variation of index of dental fluorosis with the fluoride concentration of the communal water supply. Observations on 5824 white children of 22 cities of 10 states. (Reproduced by permission from a chapter prepared by H. T. Dean in "Fluorine and Dental Health," Pub. 19 *Am. Assoc. Advancement Sci.*, 1942.)

relations are shown in Figures 46 and 47. It may be noted that fluoride concentrations under one part per million have little influence upon dental fluorosis, and that within this range, the association with dental caries is most marked.

Upon the basis of these and similar observations, it is suggested that the application of fluoride to domestic supplies deficient in that salt is a justifiable public health measure. To that end a 10-year experiment has been set up by the New York State Department of Health in two Hudson River cities, Kingston and Newburgh. These cities have similar populations and similar water supplies from upland sources. One supply (Newburgh) will be regularly treated with fluoride at a concentration of one part per million, with the other, untreated, serving as a control. A careful study of the teeth of children will be maintained during the 10-year test period.

IODINE. The element *iodine* occupies the somewhat unique position of being a rather essential impurity in a satisfactory domestic water supply. In those considerable areas in the United States where the natural waters are deficient in iodine, *endemic goiter* reaches an unusual prevalence, and a definite relationship has been established.

It was at one time thought that deficiency of iodine in the water supply alone was responsible for this serious condition and that a certain measure of responsibility rested upon the authorities for remedying such an obvious deficiency. To this end various attempts were made, as at Rochester, N. Y., to supply a small dose of iodine to the entire city through the water supply. A somewhat more conservative viewpoint, however, suggests that water is only one of the incidental sources of iodine, and that in a district in which the natural waters carry iodine there is likewise iodine in the locally produced milk and vegetables. Conversely, where iodine is absent from the one, it is likewise absent from the others. It is therefore not the particular province of the waterworks authorities to make up this deficiency, and the somewhat general use of iodized salt in the kitchen has apparently provided an adequate remedy.

LEAD. Among the heavy metals, lead is perhaps the outstanding example of an undesirable impurity. Lead is a cumulative poison, being deposited in the bone structure and inducing a serious condition known as *plumbosis* or *lead poisoning*. Plumbosis is better known as an industrial disease among painters and other workers in lead compounds than as a water-borne disease, but the combination of lead service and household piping and a lead-dissolving soft water may lead to an undesirable daily intake of lead from the water supply. This was found true, for example, at Lowell, Mass. When a change was made from the fairly noncorrosive—but highly polluted—river water to a purer but more corrosive deep well supply, a serious epidemic of lead poisoning resulted. The Public Health Service limits lead in waters to be certified for use on common carriers to 0.1 part per million.

Other Mineral Substances. There are certain possible mineral impurities of a water supply of infrequent occurrence and generally unique within strictly localized areas. Among these may be mentioned copper, mercury, selenium, and arsenic, derived in each case from local soils or mineral deposits, and concerning which nothing further need be said, except to call attention to the possibility that, in any locality in which mineral deposits of a toxic nature occur, consideration should be given to their possible occurrence in the ground waters.

A particularly instructive example is the drainage waters in the Arizona copper mine areas. It is stated that these waters, carrying rather high concentrations of copper salts, are drunk with impunity by the miners. In all such cases permissible limits must be based upon experience or upon adequate physiological experimentation. The occurrence of selenium, a highly undesirable element, in domestic water has received some study.* Available evidence tends to show that the selenium intake among persons living in "selenium endemic" regions, such as are to be found in parts of South Dakota, Wyoming, and Nebraska, is far greater in the meat, eggs, milk, and vegetables, than in the domestic water. However, a concentration of selenium exceeding 0.05 part per million constitutes grounds for rejection of a water by the Public Health Service.

Gases. Natural waters almost always contain dissolved gases. The only exceptions might be the waters of boiling springs. Water, in contact with the air, dissolves the atmospheric gases, *oxygen, nitrogen* and *carbon dioxide*. Gases, like solids, have specific solubility constants unless they enter into chemical combinations after solution; these constants, however, are uniformly inverse temperature functions. In addition, the solubility of such gases in water is proportional to the partial pressure of each gas in the atmosphere

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* M. I. Smith and B. B. Westfall, *U. S. Pub. Health Service, Pub. Health Repts.*, 52, 1375, October 1, 1937.

above, with which equilibrium is established. Gases give *life* and *sparkle* to a water, as witness the flat and insipid taste of distilled water. Carbon dioxide has special significance in connection with the corrosive properties of a water, and is dealt with in a later section.

A particularly undesirable gaseous impurity is *hydrogen sulphide,* H_2S. Its peculiar odor suggests putrefaction, with which it is generally associated, but many deep-well waters carry this gas in considerable concentration, derived from geologic sources, possibly the result of the decomposition of organic matter millions of years ago, or possibly from nature's retort within the earth. Some of the famous "baths" owe their alleged virtues to this evil-smelling gas. Patrons pay for the privilege of drinking and bathing in the *sulphur waters,* but for general domestic use they are extremely undesirable.

DISSOLVED OXYGEN: *D. O.* The presence or absence of dissolved oxygen in water is of especial significance in natural watercourses. Unpolluted streams in nature tend to dissolve atmospheric oxygen up to the so-called saturation concentration. A *saturated* solution of oxygen has just the same significance as a *saturated* solution of salt; the solution has come to equilibrium with an excess of the solute, in this case atmospheric oxygen. But, because the solubility of a gas is proportional to its partial pressure in the atmosphere above, the values which are usually designated saturation values of oxygen in water (in contact with the atmosphere) are only one-fifth those which would arise if the water were exposed to pure oxygen at atmospheric pressure.

The solubility of oxygen in water is also a function of the water temperature, and of its salinity. This latter is of importance in dealing with coastal waters. Solubility may be expressed in various units of concentration. In Table 34 values are given in two units and with reference to the effects of temperature, barometric pressure, and salinity. In sewage the solubility of oxygen appears to be about 5 per cent less than the tabulated values for fresh water.

SUSPENDED MINERAL MATTER. Clarity is a desirable quality in a drinking water. Its converse, *turbidity,* is measured optically by its interference with the transparency of the water. Turbidity may be due to organic impurities, but it generally represents clay or some similar finely divided mineral matter which settles out only slowly, or which may remain in almost permanent suspension.

Turbidity, without further chemical description, may possess any

TABLE 34

SOLUBILITY OF OXYGEN IN FRESH WATER

(*a*) In parts per million
(*b*) In milliliters per liter

Temp.		Dissolved Oxygen		Temp.		Dissolved Oxygen	
°C	°F	(*a*)	(*b*)	°C	°F	(*a*)	(*b*)
0	32.0	14.6	10.2	15	59.0	10.2	7.1
1	33.8	14.2	9.9	16	60.8	10.0	7.0
2	35.6	13.8	9.6	17	62.6	9.8	6.8
3	37.4	13.5	9.4	18	64.4	9.6	6.7
4	39.2	13.1	9.1	19	66.2	9.4	6.5
5	41.0	12.8	8.9	20	68.0	9.2	6.4
6	42.8	12.5	8.7	21	69.8	9.0	6.3
7	44.6	12.2	8.5	22	71.6	8.8	6.2
8	46.4	11.9	8.3	23	73.4	8.7	6.1
9	48.2	11.6	8.1	24	75.2	8.5	5.9
10	50.0	11.3	7.9	25	77.0	8.4	5.8
11	51.8	11.1	7.7	26	78.8	8.2	5.7
12	53.6	10.8	7.5	27	80.6	8.1	5.6
13	55.4	10.6	7.4	28	82.4	7.9	5.5
14	57.2	10.4	7.3	29	84.2	7.8	5.4

Gas volumes, (*b*), are at standard conditions, 0° C and 760 mm.

Correction for barometer: multiply by $\frac{B}{760}$, $\frac{B}{29.92}$ or $\frac{B}{1013}$, for barometric readings in millimeters, inches, or millibars, respectively.

Correction for salinity (sea water): multiply by $\left(1-\frac{S}{100{,}000}\right)$, S being salinity in parts per million of chloride.

From *Stream Sanitation.*

of the undesirable qualities of its chemical components, but, as these are separately determined and recorded in a water analysis, turbidity by itself relates merely to the appearance and acceptability of the water but with one further hygienic significance. When found in a water which, judged by its history, should be clear, turbidity usually suggests some fault or failure in the protective device. A well water, normally clear but suddenly becoming turbid after a heavy rain, should be investigated. There is probably a wornout or otherwise defective casing permitting the entrance of surface drainage. Similarly, turbidity in a filtered water suggests defective operation.

CORROSION OF METALS

Many waters have a tendency to corrode metals. If this tendency is excessive it lessens the value of the water for domestic and industrial uses and may have definite hygienic significance. This corrosive tendency of a water is known as its *aggressiveness*. It is determined primarily by chemical composition of the dissolved impurities; temperature plays an important although secondary role.

Corrosion is most frequently observed in connection with iron mains, tanks, and service pipes. It results in the production of so-called *red water,* in tuberculation or incrustation of water mains by spheroidal growths of deposited iron oxides and, in extreme cases, in complete *clogging* of the smaller piping systems. The disadvantages of red water are obvious. Tuberculation and clogging reduce the capacity of mains; necessitate frequent cleaning; and eventually cause leakage, weakening, and breakage. Corresponding action upon lead service pipes leads to solution of the lead with serious possibilities, as noted previously.

THE ELECTROCHEMICAL THEORY. The basic process of corrosion is the electrochemical solution of the metal, as was shown by Whitney.* Every metal possesses a solution tendency, measured as an electromotive force, by which free ions, positively charged, tend to leave the metal and pass into solution. This tendency is a property of the metal itself, as well as of the composition of the water. The solution potentials for certain metals are shown in Table 35.

Solution potentials are enhanced by acidity, *p*H, and are somewhat related to the mineral content of the water. The researches of Baylis and others have shown that the aggressiveness of a water is associated primarily, not with any specific concentration of hydrogen ions, but with the condition of equilibrium in the system, calcium carbonate–calcium bicarbonate–carbon dioxide.

This is well illustrated in the fact that ordinary distilled water, containing as it usually does a very little carbon dioxide, is highly aggressive toward most metals. This equilibrium is discussed more fully later.

When any clean metal surface, of iron, let us say, is placed in contact with water, solution begins at once. The solution of positively charged metal ions quickly brings the surrounding liquid layer into electrical equilibrium with the metal. This would stop

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* Willis R. Whitney, *J. Am. Chem. Soc.*, 25, 394, 1903.

TABLE 35

SOLUTION POTENTIAL OF CERTAIN METALS

Metal	Solution Potential, Volts
Calcium	−2.70
Aluminum	−1.28
Zinc	−0.76
Iron	−0.43
Lead	−0.12
Tin	−0.01
Hydrogen	0.00
Copper	+0.39
Gold	+1.30

The signs are arbitrary. As used here they represent the potential of the metal with respect to the solution and all relative to the corresponding potential of the "normal hydrogen electrode." The more negative metal has the greater *solution tendency.*

further escape of metal ions in the absence of some compensating electrolytic effect. If there are any copper ions in the water, these, having a lower solution potential than iron (see Table 35), will be plated out, and the solution of iron will continue. This phenomenon can readily be demonstrated by immersing an iron nail in a solution of copper sulphate. In the absence of any such metal ions, hydrogen, always present as dissociated H^+ ions and likewise having a more positive solution potential than iron, becomes unstable at the surface and is deposited. Again the process would seem to have blocked itself by the deposit of a protective nonconductive film of hydrogen on the metal, and, if this were a stable condition, such would be the true situation. If, however, the hydrogen becomes dissolved in the water, or, what is more important, if the water carries dissolved oxygen sufficient to oxidize the hydrogen as fast as it is formed, then (within certain limiting *p*H values) solution proceeds continuously.

This, briefly, is the electrochemical theory. There are, however, many complications. A protective coating of zinc, for example, retards solution of iron, because of another electrochemical property of metals by virtue of which they resist hydrogen deposition. This is the "overvoltage." Despite the greater solution potential of zinc, it is more stable because of a much higher overvoltage, which is, in fact, almost equal to its solution pressure, so that the two neutralize.

Dissimilar metals in contact, such as brass fittings on iron pipe, provide a galvanic cell; given a sufficiently conducting water, electrolytic solution of the more electronegative metal takes place. Even dissimilar portions of the same metal, such as will result from inclusion of mill-scale or other foreign bodies, may set up local galvanic currents.

The metal dissolved from a pipe may be precipitated *in situ* and form a protective coating sufficient to retard further solution. The weathering of copper or of lead in the atmosphere is an example of this effect. Similar reactions take place under water. Iron may be oxidized at the point of solution, but the coating is generally porous, and easily washed away. Insulating coatings, such as asphalt, are protective by preventing contact in the first instance, and also by preventing the setting up of local electric circuits.

AGGRESSIVENESS OF WATER. Viewed from the standpoint of water composition or quality, corrosion of metals is related to the *aggressiveness* of the water. In recent years this property of aggressiveness has been identified, in part at least, with the solubility relations of calcium carbonate. The normal carbonate, $CaCO_3$, is only slightly soluble in water. In the presence of carbon dioxide, however, it becomes much more soluble through the formation of the bicarbonate.

$$CaCO_3 + CO_2 = Ca(HCO_3)_2$$

Acidity or hydrogen ion concentration increases the solution tension of metals, that is, the electromotive force by which metal ions are forced into solution, thus rendering them more soluble. If, as is normally the case, the *p*H of the water results from carbon dioxide, its influence is largely determined by a complex equilibrium among the calcium salts, the carbonate and bicarbonate radicals, and the free CO_2. If the water is oversaturated with calcium in the sense of this equilibrium, it carries an excess of normal calcium carbonate, $CaCO_3$, and tends to form and maintain a coating of the carbonate upon the pipe structure. This is protective. If, on the other hand, the CO_2 is in excess, the tendency is in the direction of solution of the metal, although the relation here is complicated by other considerations. It might appear that an equilibrium condition exists at which there will be neither deposit nor solution.

LANGELIER'S INDEX. Langelier* has proposed a measure of this

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* W. F. Langelier, *J. Am. Water Works Assoc.*, **28**, 1500, 1936.

equilibrium condition and of departures from it, which he terms the *calcium carbonate saturation index.* The derivation of the index involves consideration of the mass laws associated with the mutual interrelationships of hydrogen, calcium carbonate, and bicarbonate ions, and of temperature and of total ionic concentration (of all dissolved salts).

Briefly stated, the Langelier index is

$$pH - pH_s = \log \frac{1}{H^+} - \log \frac{1}{H_s^+} = \log \frac{H_s^+}{H^+}$$

in which H_s^+ is the hydrogen ion concentration which the water would have if, at its existing composition, it were saturated with $CaCO_3$; and H^+ is the actual existing concentration of hydrogen ions. An index of zero, ($pH = pH_s$), denotes a water which is, in fact, just saturated and which will neither dissolve nor deposit $CaCO_3$. A positive value shows a tendency to deposit, and a negative value, a tendency to dissolve $CaCO_3$.

The value of pH_s is related to the temperature, the total concentration of dissolved solids, the concentration of calcium ions, and the total alkalinity as determined against methyl orange indicator. A simplification of Langelier's original equation gives

$$pH_s = K + 9.3 - \log [Ca] - \log \ [Alk]$$

[Ca] being the concentration of calcium in parts per million and [Alk] the alkalinity, expressed in the usual terms, parts per million of equivalent calcium carbonate. The term K is Langelier's temperature–total solids constant, $pK_2' - pK_s'$; it accounts for the effect of temperature upon the dissociation constant of HCO_3 and upon the solubility of $CaCO_3$, and for the influence of total dissolved solids. A simplified table of values of K, computed from Langelier's more extensive table,* is here given (Table 36). This will provide all necessary accuracy for ordinary work. An excellent nomogram for the solution of the Langelier equation has been prepared by Riehl and made available by Hoover.† A simplified scale is shown in Figure 48 for solution of the relation

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* T. E. Larsen and A. M. Buswell, *J. Am. Water Works Assoc.*, **34**, 1667, 1942.

† C. P. Hoover, *J. Am. Water Works Assoc.*, **30**, 1803, 1938. In discussion of the Hoover paper, Langelier points out an error in his original table which has been corrected in the Riehl nomogram and in the table herewith.

See also Water Quality and Treatment, *Manual Am. Water Works Assoc.*, p. 252.

TABLE 36

VALUES OF K IN LANGELIER'S FORMULA

Total Dissolved Solids	K 25°C	K 60°C
0	1.94	1.36
20	2.03	1.45
40	2.07	1.49
80	2.11	1.53
100	2.13	1.55
200	2.20	1.62
400	2.30	1.72
600	2.37	1.79
800	2.42	1.84

Temperature corrections. In the range 0–25° add 0.02 to the 25° value for each degree below 25°. In the range 25–90°, add 0.016 to the 60° value for each degree below 60°, or subtract 0.016 for each degree above 60°.

$9.3 - \log[\text{Ca}] - \log[\text{Alk}]$. Read off two values of $4.65 - \log C$, C being concentrations of Ca and Alk, respectively, and add them.

The method of solution by the use of this simplified table and scale may be illustrated by an example.

Data.

Total dissolved solids	400 ppm
Ca	20 ppm
M.O. alkalinity, as $CaCO_3$	100 ppm
Temperature	20°C.
pH	7.8

Solution.

From scale, $4.65 - \log 20$		3.35
$4.65 - \log 100$		2.65
From Table 36		
400 ppm, 25°	2.30	
correction, 5° @ 0.02 +	$\underline{0.10}$	
K		$\underline{2.40}$
$pH_s = 9.3 - \log 20 - \log 100 + K =$		8.40

Saturation index $7.8 - 8.4 = -0.6$

The index being negative, there is an excess of acidity for calcium carbonate equilibrium and the water tends to dissolve iron.

With regard to the general applicability of the Langelier relation, its author pointed out originally that it measures tendencies only. In practical application, it has been found that these tendencies result in general as indicated, but the correlations are not perfect, and waters are occasionally found in which there are wide deviations from the solubility relations predicted. There are obviously interfering items in these waters which have not been properly incorporated into the generalized equations.

The solubility of the various other metals used in connection with water systems has received far less study than that of iron. The zinc lining of galvanized pipe owes its protective power in part to the formation of an insoluble adherent basic carbonate. Lead service pipes are still in common use, and the toxic nature of lead make it a matter of first importance that there should be no material solution of this metal. Here also, there is a tendency toward the formation of a protective coating, but in certain instances (see p. 287) soft waters carrying relatively high concentrations of unbalanced carbon dioxide have dissolved undesirable quantities of lead from lead service pipes.

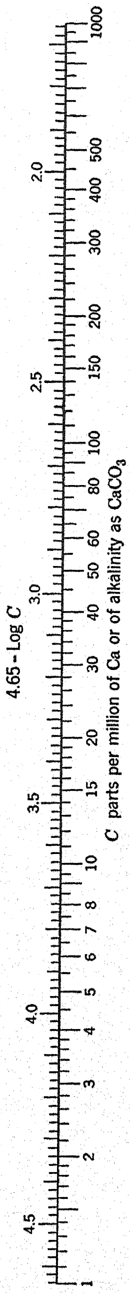

Fig. 48.

ORGANIC IMPURITIES

Classification. The impurities of organic nature commonly found in waters are the products of living organisms, animal or plant. The living bacteria and the micro-organisms are of specialized significance and are not usually included within this classification of organic matter. These are treated in a special section (p. 312).

The inert organic matters, in general, are evaluated in terms of chemical analysis. These analytical procedures are of special usefulness in the study of sewages although equally applicable to all types of waters. They are treated under Sewage Chemistry (p. 299). Finally, certain inert organic constituents, particularly those responsible for color, taste, and odor, are evaluated in terms of their contribution to the physical properties of a potable water.

Color. The *color* of a water usually results from the solution, true or colloidal, of extracts of leaves, grasses, and roots. It is an organic tea and essentially clear. A colored turbidity, such as might result from the presence of red clay, is sometimes described as *apparent color.*

Color is determined by direct comparison with standards and reported in the somewhat arbitrary terms of the color scale. Various types of colorimeters are available in which the comparison may be made against standardized glass disks or permanent solutions.

A color of 20 parts per million is just noticeable to the consumer. In many waters of New England and elsewhere colors run as high as 100 parts or more. No particular hygienic significance attaches to color *per se*. Colored waters stain the hand bowl and the laundry, but those accustomed to such waters accept them without complaint.

Permissible limits of tolerance are based wholly upon custom. Highly colored waters are unattractive to visitors, and even the local resident is generally pleased with the improvement possible with modern filtration practice. In fact, there is a distinct tendency toward improving the purely aesthetic qualities of public water supplies, especially if this be incidental to an added safeguard against minor or accidental pollution.

Taste and Odor. Certain impurities of organic nature impart definite tastes and odors to a water. These two properties are usually grouped together, for most of the so-called tastes of water are, in fact, registered through the olfactory nerves rather than through the tongue.

Tastes and odors are conspicuously associated with the growth of micro-organisms in the water. Many of these microscopic plants and animals produce aromatic substances (like the scented oils of the rose or the geranium). Although without particular hygienic significance, tastes and odors may make a water extremely unpalatable to the consumer and lead to serious public demand for relief.

Odors are rather imperfectly described by whatever suggestive terms appear to fit—sweet, musty, pigpen—and are quantitatively measured by dilution with odor-free water until the odor is just barely perceptible. A *threshold odor* of ten means that the odor is reduced to threshold or disappearing value in a tenfold dilution.

Living Organic Matter. The various forms of microscopic life occurring in waters constitute such an important class of organic impurity that their discussion is deferred to a later section (p. 312).

THE CHEMISTRY OF SEWAGE

The impurities discussed thus far have been, for the most part, normal constituents of natural waters. Our present interest in them centers in their relation to the quality of water in the incoming segment of the water contact cycle—water supply. Organic impurities in general are especially characteristic of the outgoing segment, the municipal and industrial sewages. By reason of the importance of these organic impurities in sewage treatment and in stream sanitation, we may profitably devote some time to the chemistry (including the biochemistry) of sewages.

Domestic sewage is likely to be thought of as a heterogeneous mixture of miscellaneous waste materials too complex and too variable to be measured or even described in terms of such an exact science as chemistry. To a limited extent such a concept is justified; but, just as the city itself, despite the unpredictable behavior of its individual citizens, possesses fairly constant birth, sickness, and death rates, and characteristics of youthful progressiveness or of complacent middle age, so the sewage of a community has a rather uniform chemical nature. It too is a statistical aggregate, a composite of wastes of many kinds from many sources which, when taken together and over a period of time, tends to average out irregularities of composition and disclose a definite identity.

SEWAGE CHARACTERISTICS

The application of chemical analysis to sewage has for its purpose the identification and measurement of certain characteristic properties rather than specific individual chemical components. It is thus somewhat akin to the chemical analysis of foods. In certain studies, made for special purposes, the composition of sewages has, in fact, been reported in terms of the three food groups: proteins, carbohydrates, and fats. These are themselves gross classifications and designate properties rather than specific chemical substances, but to this extent at least the domestic sewage of a community is found to be of rather consistent composition. The standard chemical determinations. Its items are selected rather to define characteristics by which sewages may be classified or compared one with another and to define their properties with regard to *sewage treatment* or *stream pollution*.

Broadly, these characteristics may be grouped under three major heads:

The chemical characteristic, *composition.*
The physical characteristic, *concentration.*
The biological characteristic, *condition.*

COMPOSITION. The composition of a sewage refers primarily to its origin. A strictly domestic sewage, for example, contains only the ordinary wastes of the household, originating in the bathroom, the kitchen sink, and the laundry, together with wastes received from such places as restaurants and commercial laundries, which may be regarded as mere extensions of the household. Additional contributions from commercial or industrial activities, not characteristic of communities in general, would not be classified as domestic sewages and might be expected to modify the sewage characteristics.

Domestic sewage, as thus defined, naturally carries reasonably uniform per capita quantities of its major constituents. Published data, especially the older records, do not appear to support this conclusion, but the more refined techniques that have been developed in recent years give evidence in favor of the reasonable assumption that *per capita* values are rather basic. It is much more likely that the recorded variations, of rather wide range have resulted from lack of accurate data as to per capita discharge, than from actual variation in per capita contribution.

Industrial wastes added to a domestic sewage augment per capita values and generally in one or another direction. That is, there will be excessive contributions of fats and proteins from an abbatoir, or of carbohydrates from a starch factory. Any such deviations, if excessive, represent modifications in the composition and the characteristics of the sewage as related to its treatment or its pollutional effect upon a receiving stream.

CONCENTRATION. The concentration characteristic of a sewage is its *strength*. We speak of a strong or a weak domestic sewage which is obviously merely another way of expressing per capita water volume. If, through lavish use or waste of domestic water, or through excessive ground water infiltration, the flow of sewage at the outfall amounts to 300 gallons per capita instead of the more usual value of 150 gallons, then the strength of the sewage will be only one-half the normal strength.

From the point of view of stream pollution, the concentration of the sewage has little if any significance. It merely means that more or less pure water accompanies whatever pollutional load is discharged. In fact, stream pollution studies may often be greatly simplified by dealing directly in terms of per capita contributions of domestic sewage and with equivalent per capita contributions of the industrial wastes, rather than indirectly by measurement of both volume and concentration.

In a domestic sewage, concentration, the reciprocal of volumetric per capita flow, is, however, a characteristic of major importance in the design of sewers and pumping station equipment and in sewage treatment processes involving such hydraulic elements as times of detention in tanks, rates of flow through filters, and loading factors in general. In brief, wherever volumetric factors enter the problem the concentration of the sewage is a significant characteristic.

In situations complicated by the presence of industrial wastes the concentration term, of course, loses its value as a volumetric index, but, when expressed in suitable analytical terms, it remains a valuable measure of filter loading and of other treatment operations. In this connection we note also what has been stated with regard to the composition of industrial wastes. Added concentration may be in terms of fats, for example, modifying the skimming problem in a primary tank; or possibly it may be carbohydrate from a starch mill imposing special difficulties upon the activated sludge process (p. 575).

Condition. The third important characteristic of a sewage is its condition. This is a composite of age, temperature, and, in some measure, degree of agitation. Active decomposition of sewage begins in the sewer and proceeds at a higher rate with higher temperature. This decomposition draws upon the limited supply of dissolved oxygen usually found in the domestic water, and anaerobic conditions may shortly develop.

Routine dissolved oxygen determinations were made upon the sewage of one of the main outfall sewers of Boston, Mass. The data for a 9-month period were plotted in the form reproduced as Figure 49.* Dissolved oxygen was present during most of the year but disappeared in July and did not reappear until September. The dotted line is purely imaginary but is suggested by the form of the curve. The suggestion of negative values during the warm weather months was borne out qualitatively by a simple experiment. Some of this sewage was siphoned into the bottom of a bottle of water of known oxygen content. An immediate determination of the dissolved oxygen of the mixture showed it to be considerably less than would have resulted had the sewage been merely devoid of oxygen. This property of anaerobic sewage was referred to at that time as *oxygen avidity*. It is better known now as the *immediate oxygen demand*.

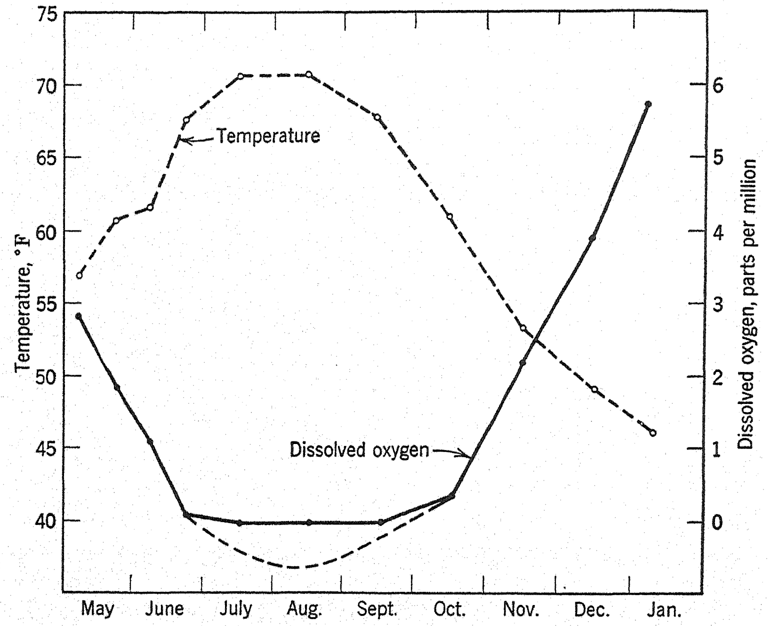

FIG. 49. Temperature and dissolved oxygen in Boston sewage.

The decomposition of organic matter in the sewer results in the disintegration of the coarser suspended matter into finer particles,

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* E. B. Phelps, *Technol. Quart.*, **18**, 40, 1905.

even down to that state commonly referred to as *colloidal suspension*. Agitation in the sewer accelerates this effect. This, in turn, affects the settleability of the suspended solids and the whole process of subsequent treatment. It also determines the manner and extent of deposition in the receiving stream, if the sewage is discharged without treatment.

Sewages are described, as to their condition, as fresh, stale, or septic. Although these terms are not closely defined, any sewage may be termed fresh if it contains dissolved oxygen. It has little odor, and the suspended matter is relatively large and largely removed by sedimentation.

Stale sewage represents the first stage of aging. It has a characteristic musty odor and an opalescent or milky appearance. Dissolved oxygen is approximately exhausted, but anaerobic decomposition has not yet become established. Suspended solids are not yet broken down, but have become more waterlogged and heavier and thus settle better than they would from the fresh sewage.

Septic sewage has developed marked anaerobic characteristics. It is black rather than grey or milky, has an odor of hydrogen sulphide, and blackens any near-by lead paint. The suspended solids are fine and settle less readily. It has an oxygen avidity which, upon subsequent discharge to a filter or into a stream, asserts itself in the form of an immediate oxygen demand.

The condition of a sewage is the characteristic which is most profoundly modified during treatment. The septic tank carries the sewage to the last stage of septicity. Modern primary treatment aims at the separation of the suspended matter with a minimum of change in condition, and oxidizing treatments of all kinds reverse the trend and proceed toward oxidation and ultimate stability.

CHEMICAL ANALYSIS

The characteristic properties of sewages are investigated in the laboratory by means of chemical analyses and certain biochemical tests. It is not our present purpose to deal with analytical techniques beyond the mere outline required to indicate the nature of the test and the significance of the data.

Nitrogen. Nitrogen is a constant constituent of most organic wastes, and the analytical determination of its various forms can be made by methods which are exceedingly delicate. In nature, nitrogen goes through the well-known nitrogen cycle (see Fig. 50), during which it is, (1) assimilated by plant life and then by animal life to become organic nitrogen; (2) decomposed by bacteria and other micro-organisms of the soil, to ammonia and amines; and, (3) oxidized by other types of bacteria to nitrite and nitrates, in which form it again becomes a plant food.

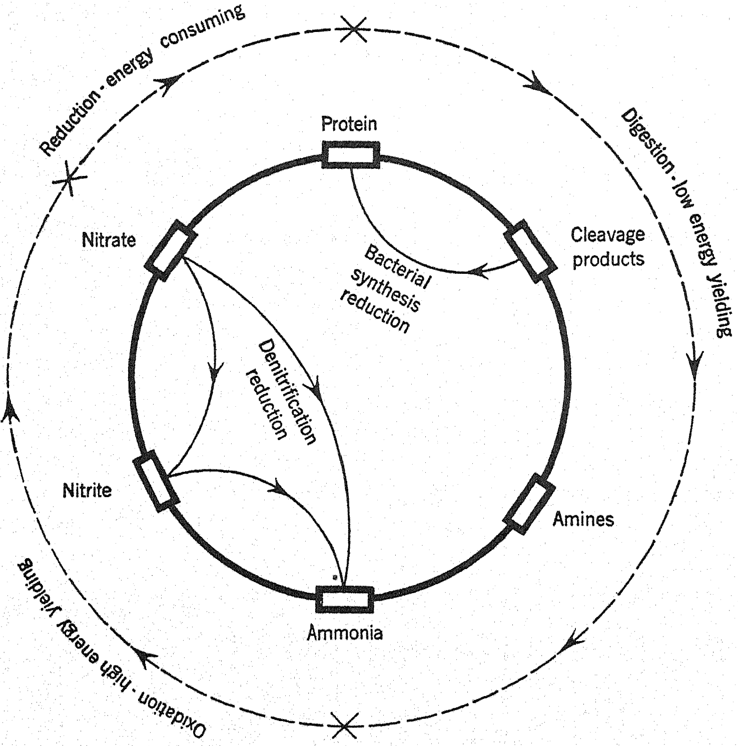

Fig. 50. The nitrogen cycle.

These various forms of nitrogen are determined or measured by certain standard procedures. The total organic nitrogen, sometimes called the Kjeldahl nitrogen, is well known to the agricultural and food chemist. It is the nitrogen of the organic substances, proteins, amino acids, and others.

Nitrogen in another form is determined as the *albuminoid ammonia,* or *albuminoid nitrogen,* a rather nondescriptive title of a property of the organic material rather than a specific analytical item. It is the ammonia recovered by distillation from an alkaline permanganate solution. The breakdown of organic nitrogen is not complete, so that the recovery of ammonia depends to a large extent upon the conditions, especially the concentration of the reagents and the time of distilling. These conditions, therefore, are carefully specified and followed in making this determination.

The third item in the analytical scheme for nitrogen compounds is the so-called *free ammonia* or *ammonia nitrogen*. This is obtained by direct distillation from a slightly alkaline solution. Like the albuminoid nitrogen, it is not a fixed quantity. The process of distillation tends to break down some of the more loosely bound organic nitrogen, and likewise carries over volatile amines. However, under standard conditions, the results represent a rather definite sewage characteristic.

Finally, nitrogen may occur in the form of *nitrite* and *nitrate*. These are the oxidized forms that are characteristic of fully oxidized sewage.

SIGNIFICANCE OF THE NITROGENS. The sum of the nitrogens provides a measure of concentration or strength of the sewage. The relative values of the various forms is a measure of condition. The change from fresh to stale to septic sewage is accompanied by a progressive weakening and breaking of the bonds which hold together the large protein molecules, releasing free ammonia and amines and increasing the amounts of both free and albuminoid ammonia released by distillation. In the older sanitary water analysis the nitrogens represented organic pollution. No distinction was possible, however, between natural pollution—soil wash—and pollution by sewage.

During the treatment of sewage by any of the oxidation processes, such as the sand filter, there is progressive oxidation yielding increasing proportions of nitrite and nitrate. These too are condition factors and, for the sand filter, the best criteria of efficiency. In less complete treatments, such as the trickling filter, other criteria are more useful. In the older scheme of water analysis nitrate represented well-purified past pollution; nitrite was regarded as a sign of danger.

THE SOLIDS. The term *solids,* as employed in a water or sewage analysis, is more properly the *residue upon evaporation*. It includes all nonvolatile substances in solution or in suspension. Filtration through an asbestos mat yields the *suspended solids*. These are ignited to give the *suspended solids—fixed,* and the difference, becomes the *suspended solids—volatile,* an approximate measure of the suspended organic matter. Evaporation of the filtrate from this operation and subsequent ignition of the residue yield in a similar manner the *dissolved solids—fixed* and *volatile,* and the sum of these items becomes *total solids—fixed* and *volatile.* Thus the complete schedule of the solids determinations becomes:

Solids		
Suspended	Dissolved	Total
Volatile	*Volatile*	*Volatile*
Fixed	Fixed	*Fixed*
Total	Total	*Total*

the italicized items being determined by sum or difference.

Progressive changes in the condition of the sewage during aging lead to disintegration and partial solution, that is, an increased proportion of soluble and of filterable colloidal material. Additional information upon this feature is obtained by another solids item frequently determined at the sewage treatment plant called the *"settleable solids."* This is the difference between the suspended solids values before and after settling for a stated period, usually 2 hours, in a cylinder. It represents that portion of the suspended solids which will settle and is thus an excellent measure of the efficiency of a primary sedimentation process. Settleable solids are also determined, as a volumetric per cent, in the *Imhoff cone.*

The total solids are a measure of concentration, and the relative proportions of volatile and fixed (organic and mineral matter) indicate such abnormalities as are due to industrial wastes, and to street wash. The suspended solids are also a very refined measure of the condition of a treated effluent in which clarity is often a required characteristic; in potable water, as turbidity they are a measure of quality.

OXYGEN REQUIREMENTS. A standard determination in the scheme of water and sewage analysis is the *oxygen consumed from permanganate.* This expanded title, from the original *oxygen consumed,* has become desirable to distinguish the item from one of entirely dissimilar nature, the *biochemical oxygen demand.* The distinction should be carefully observed.

The determination is made by boiling a portion of a water or sewage, in an acid solution, with a measured quantity of potassium permanganate, a strong oxidizing reagent. The residual permanganate is determined by titration, and the amount utilized, reported in terms of oxygen, becomes the oxygen consumed value. Like the albuminoid ammonia determination, this test does not measure any specific quantity. The results depend upon the concentration of the reagent and the time and temperature employed. The standard procedure calls for a 30-minute exposure to a standard strength of reagent in a boiling water bath.

The oxidation which takes place is confined to carbon, but even proteins contain carbon and are oxidized during treatment with permanganate, so that the test is in no sense specific for non-nitrogenous matter. However, high values, relative to the nitrogen, indicate fats or carbohydrates, presumably from industrial wastes or other non-domestic sources. The test is no longer regarded as having any significant value as an index of pollution in the sanitary water analysis.

THE BIOCHEMICAL REACTIONS OF SEWAGE

The reactions in nature, whereby organic matter is oxidized and stabilized in the stream and the soil and in many of the sewage treatment systems, are brought about by bacteria and other microorganisms, plant and animal, which depend upon the decomposition and oxidation of this "food" material for the maintenance of their own life energy.

The measures of the oxygen consumed from permanganate, obtained under the highly unnatural conditions of that test, are useful relative measures of sewage strength but are purely arbitrary and provide little or no direct information concerning the oxidizability of the organic matter under natural conditions.

It has been found, however, that stream conditions can be simulated in the laboratory and that much can be learned in a quantitative way if the normal reactions of biological decomposition and oxidation be allowed to proceed under controlled conditions. The reactions are oxidative in nature being quite analogous to combustion. There is a quantitative relation between the amount and nature of the organic matter and the amount of oxygen required for its complete stabilization under the influence of biological agencies.

We speak then of these reactions as *biochemical reactions* and of the oxygen requirement of the reactions as the *biochemical oxygen demand,* or, for simplicity, the BOD.

THE BOD TEST

The significance of BOD will best be indicated by a brief description of the nature of the test itself. Two bottles are filled from the same container with a suitable dilution of the sewage under examination. A determination of the dissolved oxygen (the atmospheric oxygen dissolved in the water) is made immediately upon one of these, and the other, tightly stoppered, is incubated for a stated period, usually 5 days, and at a standard temperature, usually 20°C. A second dissolved oxygen determination is then made upon the incubated sample. The difference, the loss of dissolved oxygen during incubation, is a measure of the demand which the portion of sewage incubated will make upon the oxygen of a receiving stream *at the standard temperature and during the ensuing 5 days.*

In the actual conduct of the test, blank tests and corrections for the corresponding demand of the water used for dilution and other refinements are imposed. The object of the test, however, is indicated in the afore-mentioned simplified procedure. It measures one of the most important characteristics of a stream, a sewage, or the effluent of a sewage treatment plant: the oxygen that must be provided by the stream during the course of further stabilization. Since the oxygen balance of a stream determines its capacity to receive and dispose of organic pollution without resultant nuisance, the BOD values yield information as to the pollutional characteristics of sewages which is not yielded by any other of the analytical procedures.

THE LAWS OF THE BOD REACTION

As stated previously, the laboratory result, under standard time and temperature conditions, is indicative of stream pollution effects under only those same conditions. Much study has been given to the BOD reaction and, although it appears to be somewhat erratic and unpredictable in single test samples, it follows, in general averages, certain well-known laws of chemical reactions with sufficient regularity and uniformity to justify referring to the resulting formulations as the laws of the BOD reaction. These laws relate to its *velocity* or rate of reaction, and to its *temperature coefficient.*

On the basis of extensive experimental work and of a statistical analysis of the results, Streeter and Phelps were able to make the following generalization:

The rate of the biochemical oxidation of organic matter is proportional to the remaining concentration of unoxidized substance, measured in terms of oxidizability.

Expressed in its differential form, this becomes

$$-\frac{dL}{dt} = KL$$

which integrates to

$$\log_e \frac{L_t}{L_0} = -Kt$$

or

$$\log \frac{L_t}{L_0} = -0.434\,Kt = -kt$$

whence

$$\frac{L_t}{L_0} = 10^{-kt}$$

In these equations L_0 is the initial oxidizability at time zero (any time during the course of the reaction, not necessarily the actual beginning), and L_t, the corresponding value at time t. The ratio L_t/L_0 is the fraction remaining, and $1 - L_t/L_0$, the fraction oxidized.

THE RATE OF REACTION. The manner in which k and t are associated indicates that k, the velocity constant of the reaction, must be defined in terms of some time unit. It has been found experimentally that, if time is taken in days, k has a value of 0.1 at 20 degrees centigrade. Since $10^{-0.1} = 0.794$, this means that, at 20 degrees centigrade, 79.4 per cent of the initial BOD remains unoxidized at the end of one day. Therefore, the rate of biochemical oxidation of organic matter of sewage origin, in the presence of an excess of oxygen and at 20 degrees centigrade, is such that the reaction is 20.6 per cent completed at the end of 24 hours; and, during each succeeding 24-hour period, the remaining unoxidized organic matter is further reduced by 20.6 per cent of its value. The progress of this geometric rate of decrease is illustrated in Table 37.

TABLE 37

THE RATE OF COMPLETION OF THE NORMAL BOD REACTION
20°C

Time, Days	Oxidized, Per Cent	Time, Days	Oxidized, Per Cent
1	21	9	87
2	37	10	90
3	50	11	92
4	60	12	94
5	68	14	96
6	75	16	97
7	80	18	98
8	84	20	99

It may be noted, as useful points of reference, that the reaction is about 21 per cent completed after 1 day, 50 per cent after 3 days, 68 per cent after 5 days, and 90 per cent after 10 days. This time relation indicates the manner in which the standard laboratory test, carried out for 5 days, may be utilized to measure the *ultimate BOD* or the value of the demand over any stated period of time. The 5-day demand is 68 per cent of the ultimate, 68/84 of the 8-day demand, and so on.

THE TEMPERATURE RELATIONS. It remains now to consider the effect of the temperature of the water upon the rate of the reaction. A simplified temperature relation, frequently employed to express the effect of temperature upon the rate of a chemical reaction, defines the *temperature coefficient* as the relative increase in the rate for an increase of one degree centigrade in temperature.

In the present instance, Streeter and Phelps adopted the value 1.047 as the best value, being the mean of several independent studies. For a rise of one degree centigrade, the velocity of the reaction is multiplied by 1.047, or increased by 4.7 per cent. The function, however, is exponential, so that the increase for a 10-degree rise is 1.047^{10}, not 10 times 1.047.

Increasing temperature likewise brings about a slight increase in the values which we have called the ultimate demand, the demand after long time, representing complete biochemical stabilization. This increase amounts to about 2 per cent per degree.

These two temperature effects and time relations have been combined in Table 38 to show the relative values of the BOD for certain specified times and temperatures over the practical working ranges.

It may be noted that these values are relative to the standard 5-day 20 degree value, taken as unity. Thus the tabular values are factors by which to multiply the standard laboratory data to convert them to any existing stream conditions. The last line ($t = \infty$) refers to the ultimate values.

TABLE 38

RELATION OF TIME AND TEMPERATURE TO THE BIOCHEMICAL OXYGEN DEMAND OF SEWAGE

Relative to 5-day 20° value, taken as unity

Time,	Temperature, °C									
Days	10	12	14	16	18	20	22	24	26	28
0.25	0.041	0.047	0.055	0.062	0.070	0.080	0.093	0.104	0.118	0.135
0.50	.080	0.092	0.106	0.120	0.134	0.16	0.18	0.20	0.22	0.26
0.75	.120	0.134	0.16	0.18	0.21	0.24	0.27	0.30	0.34	0.38
1.00	.15	0.18	0.20	0.23	0.26	0.30	0.34	0.38	0.43	0.48
1.5	.22	0.26	0.30	0.33	0.37	0.43	0.48	0.54	0.59	0.66
2	.29	0.34	0.38	0.42	0.48	0.54	0.60	0.67	0.74	0.81
3	.42	0.47	0.53	0.59	0.65	0.73	0.81	0.89	0.97	1.06
4	.51	0.58	0.64	0.72	0.80	0.87	0.96	1.05	1.16	1.25
5	.60	0.68	0.76	0.84	0.92	1.00	1.10	1.20	1.29	1.38
6	.68	0.76	0.84	0.92	1.01	1.10	1.20	1.29	1.38	1.47
7	.74	0.83	0.92	0.99	1.08	1.18	1.26	1.35	1.45	1.54
8	.81	0.89	0.98	1.06	1.15	1.24	1.33	1.41	1.50	1.59
10	.91	0.98	1.07	1.15	1.24	1.33	1.41	1.49	1.57	1.65
20	1.12	1.19	1.26	1.32	1.39	1.46	1.52	1.59	1.65	1.71
∞	1.17	1.23	1.29	1.34	1.40	1.47	1.53	1.59	1.65	1.71

From *Stream Sanitation*, where a much more detailed discussion of the BOD relations may be found.

An example will illustrate the use of this table.

The laboratory report on the examination of the sewage of a city gave a standard BOD value of 145 ppm (parts per million). The summer temperature of the receiving stream is 24 degrees centigrade, and the time of passage to the mouth of the stream under summertime low water conditions is 3 days.

The tabulated factor for these conditions is 0.89. Hence

$$145 \times 0.89 = 129 \text{ ppm}$$

But the unit parts per million loses significance after the sewage enters the stream. A more usable value will be obtained by converting to pounds per day. One part per million is equivalent to 8.34

pounds per million gallons. Hence

$$129 \times 8.34 = 1076 \text{ pounds}$$

represents the demand that will be made upon the oxygen resources of the stream, down to its mouth, by each million gallons of sewage discharged. Multiplying this value by the sewage flow in million gallons per day gives the final result in pounds per day.

The 5-day 20-degree value of the BOD is the recognized *standard value* as determined in the laboratory. The 5-day period of incubation is wholly arbitrary, selected to meet analytical limitations. The values derived have no basic significance beyond that of being related mathematically to the ultimate values.

There is a growing tendency to report these 5-day values as *the* BOD without qualification. This is erroneous and misleading. Such an expression can only relate to ultimate values. Whenever other values are reported or tabulated for use as measures of stream pollution, they should be properly identified.

BACTERIA AND MICRO-ORGANISMS

In each of the segments of the water contact cycle there are likely to be found living plants and animals ranging in size from the bacteria to fish. These are the *normal* fauna and flora of the waters. There is a tendency to restrict the use of the word *normal* to unpolluted waters or at least to those polluted only to a limited extent and by *natural* agencies. It is true that man-made pollutions are usually more severe and certainly more deliberate than those resulting from the occupation of the watershed by birds, but it is difficult to see that one is any more or less natural than the other; or that the bacteria of the human intestine are not part of the *normal* flora of domestic sewage.

In brief, our interest centers in these living forms as related to the use to which the water is being put. That which is quite normal and expected in the outgoing stream of used water, is equally abnormal and undesirable in water supply, the incoming stream. Let us consider first then the relation of the bacteria to water quality in the water supply of the community.

Bacteria in Nature. Decay in nature is always associated with the activities of bacteria and allied living forms. The bacteria are classified with the plants although, for the most part, they lack that unique property of plant life, photosynthesis, the ability to utilize sunlight as a source of energy. The bacteria derive their vital energy from the decomposition of preformed organic matter. They are nature's scavengers, the agencies of decay.

The bacteria abound in fertile fields and on wooded hillsides. They are carried into streams with the surface drainage. They are much more abundant in the richer organic media of the cesspool and of domestic sewage. The total numbers of bacteria present in a water, therefore, regardless of their kind, give an indication of the extent of organic pollution, regardless of its source.

On the whole, the bacteria are beneficient agencies performing an essential function in maintaining a balance between the organic and the inorganic or mineral worlds. As so often happens, however, the reputation of the group suffers from the acts of a few of its members. Among the bacteria, we know best those specific agencies of disease: of typhoid fever, cholera, dysentery, pneumonia, scarlet fever, and many others. Our efforts at environmental control lead us into constant conflict with these *pathogens* in air, water, and food. In the water contact our interest centers in those agencies of water-borne disease, the diseases of the intestinal tract, of which typhoid fever is typical.

HUMAN EXCRETA AND THE COLIFORM INDEX

By far the most significant and undesirable type of organic pollution of a water to be used as a source of domestic supply is that derived from human excrement. This may reach the stream by direct discharge through municipal sewers, from overflowing cesspools, or from drainage from an unsanitary privy on the hillside.

Here the danger of specific infection outweighs all other considerations, objectionable as they may be. The manifold possibilities of the presence of pathogenic bacteria are obvious, but their detection and quantitative measurement in a polluted water by laboratory procedures are both difficult and time-consuming. As a practical matter, therefore, it is held that all pollution by human excreta is potentially dangerous, and a relatively simple bacterial criterion of such pollution has been accepted as the quantitative measure of that danger.

THE COLIFORM GROUP. During the period of its development, this criterion has been variously termed *Bacillus coli, Escherichia coli, Bacillus aerogenes,* the coli-aerogenes group and, of late, merely *coliforms,* or the *coliform group.* Presumably not themselves harmful in a drinking water, these organisms are found in the intestines of warm-blooded animals and, at times, in nature apart from obvious animal pollution. Thus they are indirect rather than direct indicators of dangerous pollution, and, while the bacteriologists are engaged in the development of specific tests of increasing diagnostic value for the organisms of human origin, the sanitarian has adopted limits of permissible concentration, based upon practical experience with the use of polluted waters and with the capabilities of modern methods of water treatment. Reference is made to the subject of standards in a later section. In preparation for that discussion, it is advisable to consider some of the means by which bacterial concentrations or densities are evaluated and expressed.

THE ESTIMATION OF BACTERIAL DENSITIES

In the evaluation of the sanitary quality of water and also of milk and other foods, it is frequently desired to estimate the density of bacteria of certain species or kinds. There are several basic procedures that may be followed.

DIRECT MICROSCOPIC COUNT. A small drop of the liquid may be spread upon a glass slide, dried, fixed by heat, stained to make the bacteria visible, and examined under the microscope. As a quantitative procedure, a drop of known volume is taken and spread over a definite area of the slide. Typical fields, also of known area, are examined, and the bacteria counted. This is the *direct microscopic count.* It is a valuable technique in milk examination and has been used in studying sewage. It is most useful when the bacterial density is high.

THE PLATE COUNT. In this technique a measured volume of the fluid, diluted if necessary to reduce the actual number of bacteria to less than a few hundred, is mixed with a melted nutrient jelly which is then allowed to set and is subsequently incubated for a sufficient time to permit the growth of a visible colony from each organism or clump of organisms capable of developing under the conditions of the test. The test is restrictive, or more or less selective, for certain types and classes of organisms, according to the nature of the medium, as to nutrients and inhibiting agents employed and the time and temperature of incubation.

This technique never develops all the bacteria in a given specimen, whether it be of milk, water, or other material. The results, therefore, are purely relative. In water, as indicated earlier, they give a measure of organic pollution in general but fail to distinguish the bacteria associated with sewage from those found in the soil of the hillsides.

Some differentiation is possible through the use of special media and incubation temperatures. In the water laboratory two standard temperatures are frequently employed, 20 and 37 degrees centigrade, supposedly representative of summertime soil and stream conditions and of the body temperature, respectively. These *total counts* have so little significance in a water examination that they are being abandoned in favor of the more specific coliform tests. The Wells centrifuge technique for the examination of air is a special instance of the plate count. It is made highly selective by the use of media especially adapted to the growth of the normal nose and throat organisms.

THE DILUTION METHOD. If a fluid containing many organisms per unit volume be successively diluted with sterile water and a sample of each dilution tested for the presence or absence of organisms, by inoculating into a sterile nutrient fluid medium, a point will eventually be reached in the dilution series beyond which no growth occurs. The dilution ratio which gives this negative result obviously bears some relation to the initial density.

Decimal dilutions are usually employed in series, and results are reported as in the following example:

Dilution	0	1	2	3	4
Volume Tested	1	0.1	0.01	0.001	0.0001
Result	+	+	+	−	−

The density is apparently of the order of 100 per unit volume, rather than 10 or 1000.

THE MOST PROBABLE NUMBER: *mpn*. A more accurate interpretation of the result shown in the previous paragraph is made by assigning to it a *most probable number,* defined as the number (per unit volume or density is implied) which would be more likely than any other possible number to yield the observed result. Application of the theory of probability shows that almost any actual concentration could have yielded the results in question, as well as other results, and with determinable frequencies. But there is one singular value which would yield the result with a greater relative frequency or likelihood than any other. This value is the *most probable number* commonly referred to as the *mpn*.

Let us assume that we have liter samples of each of six waters made up to bacterial densities as indicated in the following. However well these bacteria are distributed by mixing, it is highly improbable that each measured small volume of the water will contain its exact quota. The theory of probability provides a means of evaluating the likelihood that a portion of one of these waters, of any specified volume, will or will not contain one or more bacteria; that is, will react *positive* or *negative* upon being tested. The probability of the *compound result* is the product of the respective probabilities of the five individual results listed. These final probabilities, computed for each of the six synthetic waters are as shown in Table 39.* We note then that for this particular result the density 231 per unit volume is, by definition, the most probable number.

TABLE 39

Bacterial Density (Assumed), per Unit Volume	Probability of the *Result*
150	0.659
200	0.694
231	0.700
250	0.696
300	0.682
350	0.660

THE RELIABILITY OF THE ESTIMATE. One must not be misled by the expression most probable into the belief that the mpn has any inherent probability of its own. It may be and generally is merely the most probable of a series of values, none of which has any useful individual probability.

Thus the result taken for illustration yields an mpn of 231. If the attention is confined merely to the range of values tabulated, 150 to 350, there are 200 individual values having probabilities nearly as great as that of the most probable value. Within this group, then, the probability that 231 represents the exact value of the density in the water tested is little better than 1 in 200.

Within the same range there are four groups, containing 50 values each of nearly equal probability, so that the probability that the true density lies within the range 200–250 is little better than one in four.

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* For a discussion of the mathematical relations involved see J. K. Hoskins, *J. Am. Water Works Assoc.*, 25, 867, 1933.

In brief, the single test chosen for illustration provides very limited information. It is only by the use of multiple tests and continuous examinations over a period of time that the concept of the most probable number has any valid significance.

Derivation of the Most Probable Number. The mathematical derivation of the most probable number from the laboratory findings, if these are sufficiently extensive to have any significance, is an exceedingly complicated process.* Fortunately, the relations for some of the most useful combinations of dilutions have been computed and tabulated in *Standard Methods*. Routine laboratory tests should, wherever practicable, be planned on the pattern of these tables so that the results can be readily interpreted in terms of most probable numbers.

THE MICRO-ORGANISMS

The *micro-organisms,* another important group of living things, found in water, are somewhat arbitrarily defined in waterworks practice to include several classes of plants and animals having in common only the characteristic that the microscope is necessary and sufficient for their identification and classification.

The plants are chiefly algae or diatoms; the animals, protozoa, worms, or crustacea. Typical species of most of these classes are to be found in greater or less abundance in most natural waters. When in moderate numbers they are without particular significance. Certain genera may occur in sufficient concentration to give perceptible and, at times, highly objectionable tastes and odors to the water. The particular conditions which determine the appearance and prevalence of these micro-organisms are only slightly understood. Their multiplication depends in the first place upon an available food supply, of which nitrogen in the form of ammonia or of nitrate constitutes an essential part. Ponds with muddy bottoms or drainage from swamplands are likely to develop growths, as is ground water with a high nitrate content, when exposed to the sunlight.

Lackey believes that the principal single factor contributing to large populations of *plankton,* the free floating micro-organisms, is man-made pollution. Domestic sewage, industrial and barnyard wastes and commercial fertilizers or manure spread upon the land all contribute to plankton growth.†

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* J. K. Hoskins, *U. S. Pub. Health Service, Pub. Health Repts.,* **49**, 393, 1934.

† See *Stream Sanitation.*

The algae, being chlorophyll-bearing plants, require some daylight for their development, and they multiply most rapidly in warm weather. Some of the diatoms, on the other hand, and many of the protozoa show peaks of prevalence during the winter months. These relationships are probably determined, in part, by the mutual interdependence of the various classes in the matter of food supply. Aside from these few known facts concerning the development and prevalence of micro-organisms, and frequently in apparent opposition to all the known facts, micro-organisms of one or another group have years of high or low prevalence in the same body of water, whereas lakes and reservoirs of apparently quite similar characteristics, and in the same district, may show no similarity whatever in the actual extent or variations of their microscopic life.

Many of these micro-organisms perform useful functions in the natural life of the stream. The protozoa, in particular, consume bacteria and are conspicuous in waters where decomposition of organic matter is active. Their presence and activity appear to be essential in many of the sewage disposal processes, and they are probably equally essential in the processes of self-purification of streams.

On this account the micro-organisms are of interest as *indicator organisms* of stream environment. Lackey points out that sewage itself supports certain very definite species and that these differ from the species found in the various sewage treatment works. He identifies certain other species as characteristic inhabitants of polluted streams in the typical zones: the septic zone, the zone of recovery and the clean water zone.

Routine microscopic examinations of water are made in the larger water laboratories controlling surface supplies. The methods employed and the identification of genera and their significance in relation to tastes and odors are fully described in Whipple's *Microscopy of Drinking Water*.

STANDARDS OF WATER QUALITY

We have already discussed the necessity for standards and noted that they represent, in general, imaginary lines between good and bad; necessary for the enactment and enforcement of rules and regulations, but nonetheless inadequate expressions of real facts. For these reasons it is preferable to refer to them as *administrative* *standards* and to dissociate from them any quasiauthority which they may seem to possess merely by virtue of being standards.

In response to expediency, such standards may have been drawn so far in advance as to leave negligible probabilities of danger (drinking water standards); or retarded so far as to leave no doubt of their inadequacy (slum housing). With these limitations in mind we may now summarize some of the standards employed in the definition of water quality, according to the various uses of the water.

PRIMARY AND SECONDARY USES

Bacterial Standards. The outstanding requirement for domestic water supply is freedom from pathogenic bacteria. To this end the U. S. Public Health Service standards lay particular emphasis upon the coliform density.

Briefly stated, the standard procedure calls for the testing of five equal 10-milliliter portions of each water sample. Two statistical criteria are applied to the results.

> (*a*) Of all the standard ten milliliter portions examined per month in accordance with the specified procedure, not more than ten per cent shall show the presence of organisms of the coliform group.

In addition to this requirement and in recognition of normal variability and of the fact that averages tend to conceal an occasional high value, it is further provided that

> (*b*) Occasionally three or more of the five equal ten milliliter portions constituting a single standard sample may show the presence of organisms of the coliform group, provided that this shall not be allowable if it occurs in consecutive samples or in more than
>
> Five per cent of the standard samples when twenty or more samples have been examined per month.
>
> One standard sample when less than twenty samples have been examined per month.
>
> Provided further that when three or more of the five equal ten milliliter portions constituting a single standard sample show the presence of organisms of the coliform group, daily samples from the same sampling point shall be collected promptly and examined until the results obtained from at least two consecutive samples show the water to be of satisfactory quality.

An alternative laboratory procedure, recently proposed, involves the testing of five 100- (instead of 10-) milliliter portions of each sample. The laboratory work involved is somewhat more cumbersome, but a much greater statistical reliability is achieved. In terms of this procedure, water of exactly the same coliform density as that provided for in the foregoing specification would now show the presence of coliforms in not more than 60 per cent of the 100-milliliter portions examined in any one month. The occasional occurrence of positive indications in *all five* of the test portions is also permissible under this procedure with the same restrictions as previously imposed upon the occurrence of three or more of the five (criterion *b*).

Other Impurities. In addition to these bacterial standards, the Public Health Service specifications fix upper permissible limits for certain impurities as follows:

	Parts per Million
Turbidity	10
Color	20
Lead	0.1
Fluoride	1.0
Arsenic	0.05
Selenium	0.05

Salts of barium or of hexavalent chromium, heavy metal glucosides, and other substances having deleterious physiological effects shall not be allowed in any quantity.

The following may be found in natural waters and *preferably* should not occur in excess of the following limitations, if more suitable supplies are available.

	Parts per Million
Copper	3.0
Iron plus manganese	0.3
Magnesium	125
Zinc	15
Chloride	250
Sulphate	250
Phenolic compounds (as phenol)	0.001
Total solids	500

For softened and other chemically treated waters there are various limitations upon the alkalinity and the reaction as expressed in the *p*H value, which are interrelated.

The Public Health Service standards, adopted in the first instance to facilitate Federal administrative control over waters used by interstate carriers have, by common consent, been accepted as reasonable standards of purity for municipal supplies in general. These standards recognize the almost universal presence of organisms of the coliform group in natural waters and in polluted waters which have been subjected to treatment adequate to render them safe as judged upon epidemiological evidence.

Standards of this sort are in reality tolerance limits on the one hand and expressions of the principle of expediency on the other. In 1925 the Public Health Service standard was raised from an equivalent of not more than two coliforms per 100 milliliters to its present limit of not more than one. There is little, if any, evidence that the use of waters within the range of either of these standards has ever caused disease.

The adoption of the more stringent standard was justified upon the two principles already discussed: the principle of relative purity and the principle of expediency. The first of these states that perfect safety is unobtainable and that the measure of protection obtained by any given procedure is relative, in this case determined by a quantitative evaluation of the coliform density. The rule of expediency states that within any given field of activity there are physical or economic limits beyond which it is impracticable to go in the direction of relative improvement. Administrative standards are justifiable up to these limits. With the joint application of these two principles it will always be found that administrative standards are of a temporary nature and will tend to change with improvement in the arts of prevention, as well as with growing appreciation of the values of health.

OTHER SPECIFICATIONS. Before the introduction of bacteriological techniques in the examination of water the quality of water was reported in terms of the so-called *sanitary analysis*. In addition to the tests which are still utilized in measuring such physical properties as color, turbidity, and odor, the sanitary analysis included the various determinations related to organic impurities discussed under The Chemistry of Sewages (p. 299). Some of these determinations, especially the nitrogen terms and the chlorides, were regarded as criteria of polluting organic matter, but they suffered from lack of specificity; sewage was reported in the same terms as the organic residues from a swamp water, and with little discrimination. Except for the physical items, the sanitary analysis has been largely abandoned in standard water laboratory practice and in the consideration of analytical criteria of pollution or of safety.

TERTIARY USES

Bathing Waters. On general principles, it may be granted that acceptable bathing waters should be as clean as possible and free, within reasonable limits, of evidences of sewage pollution. Proceeding from the general to the specific, however, these specifications leave a wide range for the application of official or personal judgment.

Impure drinking waters and their subsequent improvement by modern techniques have been found to be so closely correlated with epidemic outbreaks of water-borne diseases that a satisfactory basis has been provided for the establishment of minimum requirements. If the principle of expediency has justified the further application to these of a safety zone, we may still recognize a basic epidemiological factor. No such basis is to be found in the record of bathing waters.

The possibilities of an unfavorable public health reaction from the extensive use of highly polluted waters for bathing are obvious. Even salt water is taken into the mouth and nostrils; fresh water is likely to be more freely swallowed. Direct contact with the skin and with the more sensitive membranes of the nose and eyes present other possibilities. Yet we find little positive and much negative evidence in the matter of the harmfulness of bathing waters.

In New York City the regulations of the Health Department forbid bathing in the heavily polluted waters along the shores of Manhattan Island. Nevertheless, on any summer day large numbers of men and boys may be seen in these grayish waters, and the records produce little evidence, if any, of unfavorable consequences. Less extreme examples, but involving far greater numbers of persons, are to be found in several other parts of the New York area, and this is doubtless typical of other places. On this kind of negative evidence we do not, of course, approve the practice of bathing in what is obviously diluted sewage; neither do we gain much support or help from these facts for the establishment of minimum quality standards.

A Joint Committee of the Conference of State Sanitary Engineers and the Engineering Section, American Public Health Association has undertaken to gather the available information on the subject of disease transmission through bathing waters. An earlier committee, by circularizing the medical profession, had collected a considerable amount of information which may be summarized as follows:

Infections	No. of Types	No. of Cases
Eye	6	169
Ear	5	191
Nose	6	149
Throat	5	33
Skin	11	141
Venereal	2	42
Gastrointestinal	3	26
Others	2	8

Material of this sort has little validity from an epidemiological standpoint. It is, however, suggestive of possibilities. The present committee made a more direct approach, through the state health departments. Statements were obtained from 30 out of 39 states reporting, that they had no authentic records of sickness attributable to swimming pools or bathing places. In one instance an outbreak of dysentery involving 144 cases was believed to be due to bathing in polluted water, and several other minor outbreaks of intestinal nature were reported. An outbreak of impetigo, involving 15 cases, was attributed to a wading pool or to personal contact. Vague reports of eye and sinus infections had come to several of the health departments, as had one suspected case of sleeping sickness. Considerable interest was manifested in the possibilities of the transmission of skin infections, and in Wisconsin and Michigan bathers have been affected by "swimmer's itch," a dermatitis caused by the cercaria or free-swimming larval stage of a parasitic schistosome worm for which certain snails provide the intermediate host. Systematic control of the snail population of these waters (by way of aquatic growth control) has been undertaken. It must not be overlooked that skin infections may represent unsanitary conditions in general, especially in respect to bathing suits, towels, floors, benches and the like, rather than any immediate transmission through water.

In many districts, of which the New York area is typical, there may be found a continuous gradation of conditions from such grossly polluted waters as those of the lower Hudson, to the pure waters of the ocean front, remote from all possible sources of pollution. The public health question which arises is just where to draw an administrative line which will separate the reasonably safe from the definitely unsafe waters. Regulations of the various state departments of health rely, in general, upon the coliform criterion which, as we have seen, is at best a criterion of freedom from pollution of intestinal origin. In a few instances the total bacterial count is employed in addition, but this criterion is more frequently met with in connection with swimming pools.

The Joint Committee points out that existing state and city regulations appear to hit upon two widely divergent limits for standards of acceptability, one of 50 and the other of 1000 *E. coli* per 100 milliliters; and holds it "perhaps reasonable to conclude that, subject to interpretation of analytical studies from proper angles, waters better than the lower limit (1000 *E. coli* per 100 milliliter) are fairly acceptable."

A relative classification of bathing areas is recommended, rather than absolute standard of safety. In brief, as we have seen in the discussion of drinking waters and shall see in other instances, including foods, safety is relative, and maximum safety under reasonably attainable conditions, rather than total safety, is all that can be provided or expected.

Both bacteriological examinations and sanitary surveys should enter into the final judgment, although experience has indicated that, when properly done, the two are well correlated. The Joint Committee's suggested classification, to be based upon thorough sampling of an area at many stations and over the tidal period, is as follows:

Class	*E. coli* per 100 Ml
A	0–50
B	51–500
C	501–1000
D	Over 1000

By way of camparison it may be noted that even the Class *A* waters may contain *E. coli* concentrations up to 50 times the permissible concentration in drinking water. As regards the others the committee concludes:

> The interpretation of areas falling into classes *B*, *C* and *D* as to whether these areas may be considered good, doubtful, poor or very poor, must for the present be left with the interested state health department or other agency concerned.

In actual practice the available waters of any given area will generally be parceled out in such a manner that the best of them are "approved" and the worst "condemned" for public bathing, with perhaps an intermediate group left in the "doubtful" class. Until such time as there has been accumulated much more definite information as to the harmful effects of bathing in waters of any stated degree of pollution, this application of the useful principle of expediency will continue to govern.

Perhaps one distinct advantage of restricting bathing to the better waters is that we thus direct attention to the wasteful use of stream resources. Clean waters along the shores of any community have their direct aesthetic and economic appeal. If to this appeal be added the potential values inherent in their use for public bathing, the actual net cost of adequate treatment of the city's sewage will be materially reduced.

SWIMMING POOLS. The question of standards for the waters of swimming pools is greatly simplified by the fact that these waters are contained and under control. The problem here is to maintain sanitary conditions against a constant inflow of polluting matters, chiefly bacteria, from human bodies. Assuming, as is obvious, that some protective treatment is required, it becomes a relatively simple matter to maintain a high standard. To this end drinking water standards are commonly found in the regulations. Coupled with these it is not unusual to find standards for permissible total bacterial counts.

The Recommendations of the Joint Committee suggest that not more than 15 per cent of the samples covering any considerable period of time shall contain more than 200 bacteria per milliliter or show coliforms in any of the five 10-milliliter portions of water at times when the pool is in use.

An added feature in swimming pool sanitation is the desirability of regarding the water as a continuous disinfecting solution, rather than relying upon its intermittent treatment during recirculation. Thus, in pools that are chlorinated, a certain *residual chlorine* concentration becomes a measure of water quality. This must be maintained at a level which guarantees rapid disinfection of any newly added material and, at the same time, one that is not objectionable to the bathers, especially as regards irritations of the eyes or nasal membranes.

These objectionable effects begin to be felt at about 0.6 part per million with residual chlorine or hypochlorites and at about 1.0 part with chloramine (chlorine compounds with ammonia). Recent experience has indicated that, if the residual is actually free chlorine (see Breakpoint Chlorination, p. 481), much higher concentrations may be tolerated.

WATER FOR THE GROWING OF SHELLFISH. The importance of the shellfish industry and the ease with which disease may be transmitted through shellfish taken in polluted waters have led to extensive studies of the problem and to special standards for shellfish-growing waters. Standards have been promulgated by the United States Public Health Service in the following form.

A minimum requirement for state and Federal approval of an area for growing shellfish is a satisfactory showing upon sanitary survey. The survey takes into account the amount of pollution of tributary waters, opportunities for natural self-purification before reaching growing area, degree of dilution, and bacteriological evidence of residual pollution over the area. Tentatively, a bacteriological standard of 70 per 100 milliliters of water has been set as the upper limit of permissible coliform concentration. This applies to the median value of an adequate series of samples well-dispersed over the area and through the tidal period and the season.

If an area is obviously subject to gross pollution or even to slight pollution, if from near-by sources, or if bacteriological examinations indicate a coliform concentration in excess of 700 per milliliter (mpn of median value of a series of samples), the area is classified as *grossly polluted* and may not be used as a growing area.

Waters intermediate between these two classifications are designated *moderately polluted restricted*. Under certain restrictions oysters may be taken from such areas during the period of hibernation, if the water temperature remains consistently below 41°F and if the coliform content of the oysters so taken does not exceed 20 per milliliter. Shellfish may be taken from polluted areas for re-laying, a matter discussed in Volume II.

NUISANCE AVOIDANCE. Nuisance, in the restricted sense in which the word is usually employed in reference to a stream, means primarily a condition of a stream which is offensive to the sense of smell; a secondary and associated type of nuisance is unsightliness and foul appearance of the stream and its banks. These conditions are not usually measured in terms of laboratory analysis. A rather sharp chemical criterion of nuisance, however, is the absence in the degradation of the stream under increasing pollution loads, is marked by the downward trend of its dissolved oxygen values.

It is not necessary, for the production of nuisance, that the entire body of water be devoid of oxygen and subject to the reactions of anaerobic decomposition. Deposits of sewage sludge upon the bed and banks of the stream are intrinsically anaerobic, and decomposition with its inevitable accompaniment of noxious gases (hydrogen sulphide and others) and dark discoloration will occur therein. According to the balance between the extent of this decomposition and the concentration of dissolved oxygen in the overlying layer and the depth of that layer, the gaseous products of decomposition may or may not escape to the outer atmosphere. The mechanism of the oxygen balance of a stream is more fully discussed in chapter 12.*

Nuisance may have a much broader meaning than that implied in malodorous and unsightly conditions referred to insufficient oxygen. Subjectively, the commission of a nuisance results from any act or process which materially detracts from the value of the stream for any intended use. A heavy deposit of mineral silt from dredging operation, leading to deposits behind mill dams; the discharge of industrial wastes which are oily, highly colored, malodorous, or strongly acid or alkaline; the discharge of phenol or any of its homologues into a domestic water supply later to be chlorinated; and any discharge likely to harm aquatic life may result in nuisance and be legally enjoined. For all these, however, there is but one standard, the nature and extent of the resultant harm.

FISH LIFE. Various elements of the normal aquatic environment of fish are affected by stream pollution. Chief among these, and most commonly mentioned, is the supply of free oxygen, normally available as dissolved oxygen; this may become so seriously depleted as to interfere with respiration. Minimum oxygen requirements vary widely with fish species; they increase with rising temperature and are greater at the spawning period than normally. The eggs and the young fry are more susceptible than the adult.

Less well recognized, except by fisheries experts, are certain other effects of pollutions, especially industrial pollutions. Various specific wastes have been studied by the U. S. Bureau of Fisheries.† Ellis‡ has summarized these and other findings in defining five classes or groups of components hazardous to fish life.

1. Suspensoids which blanket or cover the stream bottom and submerged objects.
2. Substances having an oxygen demand.
3. Compounds altering the *p*H of the water.
4. Materials increasing or changing the salinity.
5. Specifically toxic substances.

Bottom blankets (of such materials as sawdust) smother the bottom *biota* (plant and animal life) so important for fish food. A high oxygen demand upsets the oxygen balance of the stream and may lead to oxygen depletion (p. 291) below the level necessary to support fish life. Fresh water fish require about 5 parts per million of dissolved oxygen. Although they may be found in waters of lesser oxygen content, they are not prospering, the formation of reproductive cells is reduced or stopped, and the fish's susceptibility to metallic poisons and other hazards is greatly increased.

Fish and the common aquatic organisms are most successful in waters having *p*H between 6.8 and 8.4. Wastes more acid than *p*H 5 or more alkaline than *p*H 9 range from detrimental to lethal. Seemingly trivial changes in *p*H also appear to throw out of balance the temperature and dissolved oxygen tolerances.

Salts and brines, such as are discharged in large quantities by oil well operators, may produce an unfavorable osmotic change to which, if it is sudden, fish are unable to respond. Toxic substances, more commonly the salts of the heavy metals, are often the critical component of an industrial waste. Their action upon fish and the fish food life of the stream needs no detailed discussion.

Hubbs* also emphasizes the importance of the indirect effect upon fish food. Any disturbance of the natural balance of plant and animal life in the streams or lakes may seriously affect the fish life. This indirect effect in depleting or eliminating the fish supply may well be more important than the direct killing effect.

He points out, however, one beneficial modification of the natural balance. Artificial fertilization of waters is commonly practiced in experimental and controlled fish ponds and within reasonable limits, organic pollutions, otherwise harmless, are known to increase fish populations.

Grindley† has investigated quantitatively the toxicity to rainbow

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* C. Hubbs, *Sewage Works J.*, 5, 1033, 1933.

† J. Grindley, *Ann. Applied Biol.*, 33, 103, 1946.

trout and minnows of certain chemical substances including arsenites and arsenates, chromates, zinc sulphate, ammonium salts, and the organic salts sodium picrate and sodium dinitrophenate. He also describes suitable methods of making toxicity tests and the necessity of controlling and evaluating such variables as temperature, oxygen concentration, and *p*H.

Anderson* has investigated the toxicity thresholds of various substances found in industrial wastes and proposed a simplified technique involving the immobilization of the microcrustacean *Daphnia* (the water flea) as a test.

The New York State Conservation Commission employs the *minnow test* as an over-all criterion of water quality. Under standard conditions, the ability of these small fish to survive in water has been found to serve as an excellent screening test to separate the reasonably pure from the unfit waters.

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* B. G. Anderson, *Sewage Works J.*, **16**, 1156, 1944.

CHAPTER 11

WATER SUPPLY

Having dealt with water quality and its general relations to the various uses of water throughout the contact cycle, we are now in position to consider in more detail that single segment of the cycle which carries water from the stream source to the consumer—the water supply system. Water supply involves the gathering, protection, storage, purification and distribution of water for domestic, industrial, and other uses.

THE COMMUNITY WATER SUPPLY SYSTEM

A TYPICAL LAYOUT

A schematic layout of a typical water supply system with its principal component parts is shown in Figure 51. This may be regarded as a composite picture, one or another portion of which may not be found in any given situation. The source is a common one for surface supplies, a distant, protected, upland *watershed,* a dam and *storage reservoir.* From here the water is delivered by gravity through a long aqueduct to the site of the *treatment works.* (Alternatively, we might have shown a near-by lake, stream or well and a pumping station.)

After passage through the treatment works where the concentration of any harmful or objectionable impurities has been reduced to acceptable limits for primary use the water is ready for delivery to the consumer. The principal supply lines are duplicated to insure against a break in the service in case of accident or otherwise.

The *distribution system* is an interconnected network or grid of pipe ranging in size from the larger feeder mains to the service mains in each street. The latter are tapped for each individual service.

Valves at various junction points permit the closing off of any section for repairs or in case of breaks, and the grid system provides for detouring the water around any such cutoff. The familiar fire hydrants are spaced along the street curbs at intervals depending upon the fire protection requirements of the area.

Elevated distribution reservoirs or tanks, located near the areas of heavy demand, provide adequate pressure during the hours of heavy draft, and enough storage for such an emergency as a major fire or a break in the main supply line.

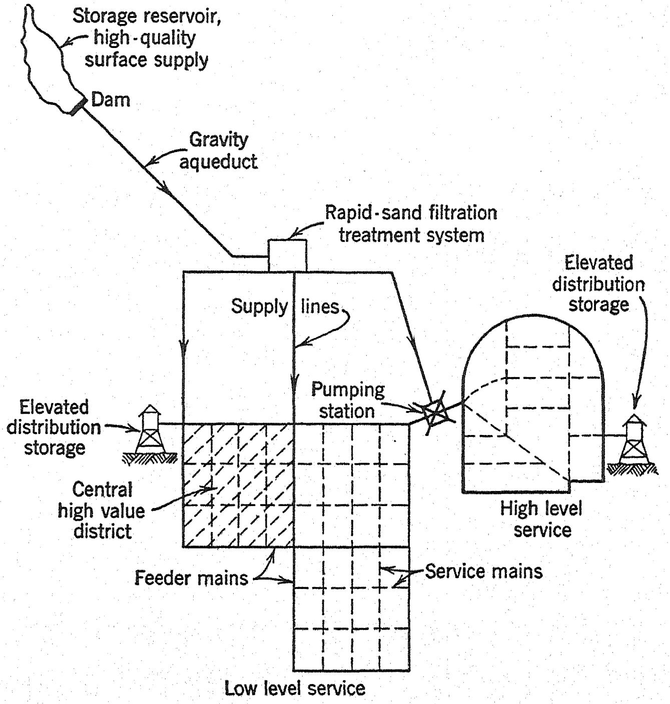

FIG. 51. Schematic water-supply system.

The topography may be such that a portion of the city is located at a high elevation which cannot be served by gravity. The areas which can be served by gravity flow are then referred to as the *low level service district* and the areas at the high elevation, the *high level service district*. The high level district is served by a pumping station which elevates the water to that portion of the distribution system including a high service distribution storage tank.

COMPLEXITIES OF METROPOLITAN WATER SUPPLY SYSTEMS

The water supply systems serving the large populations of metropolitan districts are more complex. Such districts generally overflow the political boundary lines of the central city and include a number of peripheral satellite communities which, although retaining separate political identity, are, in fact, a part of the same economic and biological unit.

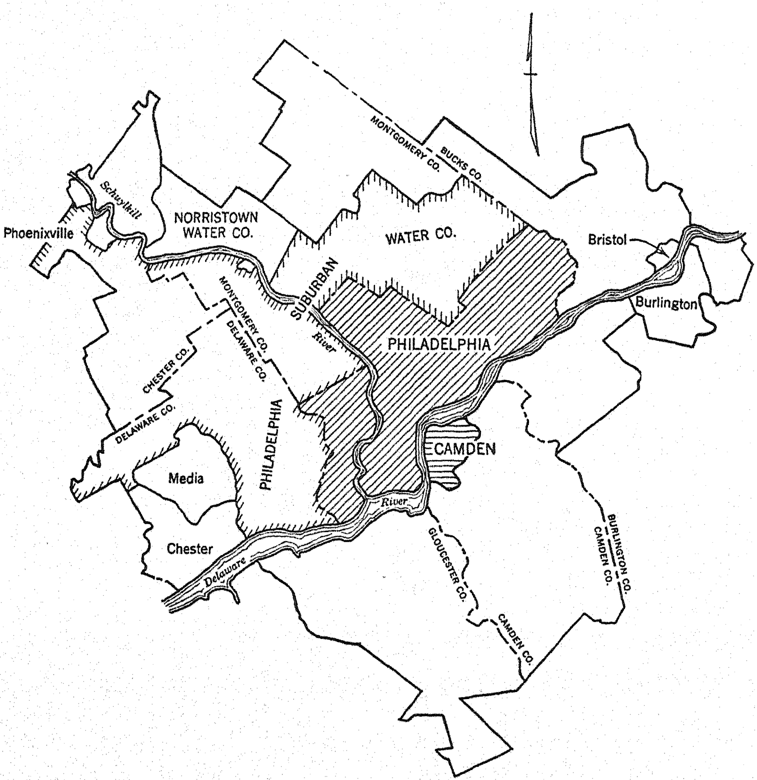

Fig. 52. Philadelphia metropolitan district major water-supply systems. District population, 1940—2,898,644. 163 civil divisions. 100 organized water-supply systems. 402 million gallons per day average 1941 consumption.

In some instances, with leadership and foresight, the water supply problem was initially developed as an integrated system to serve an entire metropolitan district, such as the Boston Metropolitan Water Supply and the great developments in California serving the Los Angeles Metropolitan District and the San Francisco–Oakland area. On the other hand, many of the large metropolitan districts are served by a complex arrangement of separate systems for each political unit, both privately and publicly owned and operated.

An example of such development is the multitude of systems serving the Philadelphia–Camden Metropolitan District, shown in Figure 52. Approximately 3,000,000 persons are served in 163 civil divisions by 100 separately organized water supply systems, one half publicly owned and supplying 90 per cent of the population in the central cities, and the remainder privately owned, principally in the civil divisions fringing the central cities. The problem of integrated efficient service for metropolitan districts is not peculiar to water supply alone; it follows through the remainder of the water contact cycle in sewage and industrial waste treatment and disposal and stream control, as well as many other environmental services, in addition to the water cycle. Integration and orderly development for the great urban centers by logical *Service Areas* is a challenge to the public health engineer in the art and science of environmental control.

WATER CONSUMPTION

QUANTITIES OF WATER REQUIRED FOR PRIMARY AND SECONDARY USES

In addition to a safe quality of water for primary use, we are concerned with adequate quantity and reliability of continuous service. Inadequate supply or breakdown in service introduces a grave public health danger from the promiscuous use of other unprotected unsafe sources.

The quantity of water consumed for primary and secondary needs varies so radically from place to place that reliable estimates cannot be made from generalized data. Each community is a study in itself, and requirements are established from a detailed analysis of many local factors.

Table 40 gives a general idea of the average quantities of water required for various purposes.

TABLE 40

COMMUNITY WATER REQUIREMENTS

Use	Reasonable average gallons per capita per day for composite community
Residential*	40
Commercial	15
Industrial	30
Public	10
Losses	15
Total	110

* Bare minimum essential for residential (piped system), gallons per capita per day:

Drinking & culinary	4
Laundry	6
Bathing	5
Toilet (2 flushes)	5
Total	20

FACTORS INFLUENCING CONSUMPTION. The important factors which influence consumption of water and are responsible for wide variations among communities are size; type: residential, commercial or industrial; the nature of the water supply system: high or low pressure, metered or unmetered services, good or poor maintenance of the distribution system and water waste surveys; economic conditions: depressions or booms. Other factors influencing consumption, generally less significant, are quality of the water supply; climate, hot weather involving modern water-cooled air conditioning; the rates charged for water, and the economic status of the inhabitants.

Larger cities have a higher per capita consumption than smaller, although combination of other factors may reverse this. Commercial and industrial cities may have high per capita consumption rates because of the demands of industry for process water. The proportion of zoned area, residential, commercial, and industrial, has an important bearing, likewise, on the demands in different parts of the same community. In some cities industrial demand dominates consumption and, varying with economic conditions which are difficult to forecast, may cause radical variation in needs from time to time (see Figure 53).

Systems that are well maintained, particularly if they are metered and systematically surveyed for waste have substantially lower per capita consumption rates than those not so well controlled. High pressure increases consumption, largely through increased waste and leakage. High cost of water inhibits consumption, the more so in communities of low family income.

Liberal use of water in the home and in the community is to be encouraged, not only for drinking, culinary, laundry, and bathroom uses; but also for swimming pools, and for beautifying the environment in parks, lawns, and gardens. The practice of restricting lawn sprinkling may be justified in emergencies, but it should not remain a policy. Man is essentially an outdoor creature and in his confined highly urbanized living needs every encouragement to develop his outdoor environment. Water, unlike air, cannot be free; but it should be provided at the least possible cost to the consumer. On the other hand, wanton waste and leakage serve no human need.

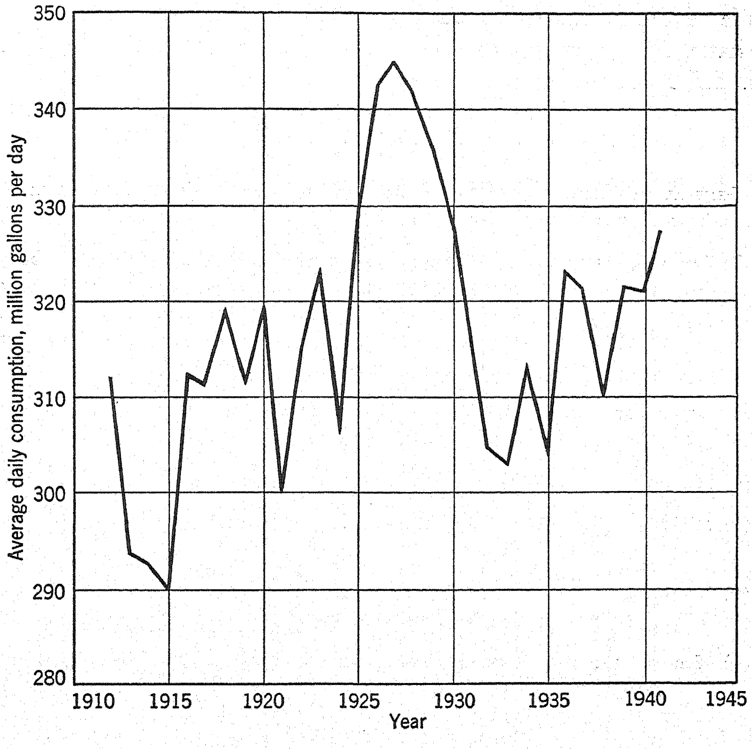

FIG. 53. City of Philadelphia average daily water consumption, million gallons per day.

VARIATIONS IN RATES OF CONSUMPTION. In addition to these factors which determine the general level of the water consumption by the community, the *rate* of consumption (per capita consumption per hour or per day) fluctuates from year to year, from season to season, from day to day, and from hour to hour, depending upon the habits and activities of the population. In fact, the pattern of life of the human community is inscribed upon the water meter charts. The general pattern of variations in the rate of consumption at different time periods is indicated in Table 41.

TABLE 41

GENERAL PATTERN OF VARIATION IN PER CAPITA RATE OF WATER CONSUMPTION

(1) Year to year	Tendency toward an increase, but not always clearly defined.
(2) Season to season	Highest during the summer at 120–140% of the yearly average; Lowest during late winter at 70–90% of the yearly average. (In cold climates where services are not metered, winter rates may be above the yearly average as a result of allowing taps to flow to prevent freezing.)
(3) Day to day	Generally lowest on Sunday; highest on Monday (wash day); fairly uniform during the week.
(4) Mean daily	Average of all days of record over a period of years.
(5) Minimum daily	The minimum day of record over a period of years; 60–80% of the mean daily.
(6) Maximum daily	The maximum day of record over a period of years; 150–200% of the mean daily.
(7) Hour to hour	Minimum in early hours of the morning, 40–70% of the day's average; maximum in the forenoon, 120–170% of the day's average. (On maximum days during hot summer a secondary hourly peak may occur in the late afternoon as a result of heavy lawn sprinkling, but this is not the usual hourly pattern.)
(8) Minimum hourly	The minimum hour on the minimum day; 35–60% of the mean daily.
(9) Maximum hourly	The maximum hour on the maximum day; 200–300% of the mean daily.

FIRE DEMAND. The total quantity of water required for fire protection during a period of a year is small in comparison with that required for normal functions of a community, but for short periods during fires water must be delivered at a high rate. In all but the large metropolitan districts the rate of demand for fire protection is the deciding factor in determining the capacities of pumps, distribution reservoirs, and mains. The peak fire demand can be expressed as a function of population, ranging from a minimum of 1000 gallons per minute for communities of 1000 population to 12,000 gallons per minute for population of 200,000.*

The probability of occurrence of a major fire during the maximum hour of the maximum day is slight. It is customary to add the fire demand to the normal demand of the maximum day, or, say, 1.6 times the mean daily demand. Thus, for a city of 40,000 having a mean daily demand of 100 gallons per capita, the pumping and distribution system would be designed for:

	Million Gallons per Day	Gallons per Minute
Normal demand, 40,000 × 100 × 1.6	6.4	4440
Fire demand, 24 Standard fire streams		6000
Total		10,440

At this rate a 10-hour fire would require 3.6 million gallons of water in addition to the normal flow.

ESTIMATING FUTURE REQUIREMENTS. Since water consumption is usually expressed in gallons per capita per day, estimates for future requirements are dependent upon population and rate per capita and thus involve a prediction of future population. The period for

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* Recommendations of the Board of Fire Underwriters.

For communities of less than 200,000 the peak fire demand in gallons per minute Q is given by

$$Q = 1020\sqrt{P}\,(1 - 0.01\sqrt{P})$$

P being the population in thousands. Q, however, is usually expressed as the number of standard 250-gallon-per-minute fire streams.

The normal duration of a fire for communities of over 2500 is 10 hours and for communities of less than 2500, 5 hours.

The fire demand for a district may be greater or less than the peak demand for the community as a whole, according to its congestion. It may be taken (in gallons per minute) at

Small single-family units, sparsely built up,	500
Two-story residential, built up,	1000
High value residential, closely built up,	1500–3000
Apartments, densely built up,	4000–6000

which excess capitalization is provided for future growth will vary with the size of the system and also among the different portions of the system. With the passing of the era of rapid expansion and the trend toward stabilized population, extreme care must be exercised in estimating future needs, or funds may be invested in facilities for population which will not exist. Planning for long periods in advance (50 to 100 years) is highly desirable, but construction should be designed for flexibility, with small excess capitalization (15 to 25 years) and provision for systematic additions as demand demonstrates the need therefor.

SOURCES OF WATER

The primary source of fresh water at the earth's surface is precipitation. The annual rainfall and its seasonal and geographic distribution constitute major factors in the determination of the habitability of regions of the earth for man (see chapter 9).

At and within the earth's surface water is gathered into several typical bodies or formations. For convenience in treating of water supply we distinguish waters of the following classes:

- Surface waters:
  - Rivers.
  - Lakes.
  - Impounding reservoirs.
- Ground Waters:
  - Shallow wells.
  - Deep wells.

The distinction between ground and surface waters is somewhat arbitrary. Most surface streams are fed by ground water *springs* at their upland sources and along their banks; and many large rivers have corresponding underground streams into which some of them disappear completely during droughts. In the drainage area of any inland lake system, like the Great Lakes, the underground flow is toward the lake basin where it emerges as surface water. Nevertheless, regarded as water supply sources, ground and surface waters constitute distinct types with certain definite characteristics associated with their past history.

Selection of a source of water involves considerations of intended use or uses. A supply which may be of suitable quality for certain industrial purposes may be wholly unsatisfactory for public consumption. Again, a ground water supply may be sufficient in quantity for a small community but not for a large city or metropolitan district. The selection of a major supply for domestic and municipal uses often involves technical, legal, and financial considerations; frequently, the legal and financial aspects determine the choice rather than the strictly technical features.

Furthermore, the selection of a particular source of supply, although a matter of major importance, is not final. Sources near at hand are utilized while a community is small and later abandoned because of inadequate quantity or degeneration in quality. Adequacy of source, therefore, changes with time and circumstances.

SURFACE WATER SOURCES

Quality. In general, surface waters are likely to be *turbid* or *colored* although these are not invariable characteristics. Surface waters are, however, invariably *polluted* or *subject to pollution* and thus require treatment before use. In the larger cities recourse must generally be had to surface waters; these likewise provide the most economical source for many smaller places.

In addition to its ready availability in large quantities a surface water has one feature which is always in its favor. Its history is or can be, rather definitely known. If it shows evidence of organic impurities, inspection of the watershed will disclose the source of the impurity and provide definite information as to its significance. The presence of considerable numbers of coliforms, for example, might be accepted with complacency in conjunction with a sanitary survey which disclosed no human occupancy of the watershed but a considerable area of pasture land in its upper reaches. An identical laboratory finding might be alarming if the stream received the immediate drainage of farmhouses where the sanitary arrangements were found to be primitive.

The possibility of making a sanitary survey of the watershed of a surface water supply makes it feasible in general to institute corrective measures. Officials of the state departments of health or of the water department generally have jurisdiction over the watershed area to the extent that they may inspect and control the provisions for the disposal of domestic sewage and farm or industrial wastes.

GROUND WATER SOURCES

Natural Impurities; Mineralization. One consequence of the storage of ground waters in close contact with the soil and rock is that they themselves have become part of the geological formations. As such they have come into solubility equilibrium with the mineral constituents of the earth's crust. Even the granites have definite solubility coefficients while such minerals as *gypsum* (calcium sulphate), *calcite* (limestone or calcium carbonate) and *dolomite* (magnesium carbonate) are sufficiently soluble to impart new characteristics to the water; the more so as the solubility of the carbonates is enhanced by acidity.

Acid conditions, in turn, are established by the decomposition of organic matter in the upper soil layers and the solution of the resultant carbon dioxide (carbonic acid). Various iron and manganese minerals are also somewhat soluble in acid waters, particularly in the absence of oxygen.

Ground waters may also be expected to carry in solution other characteristic minerals of the region. The ground waters of the copper mining districts of Montana, for example, as taken from the deeper mines, run high in *copper,* and the mine drainage waters of the coal mines of West Virginia are heavily laden with *iron* and *sulphuric acid* derived from the pyrite deposits. *Selenium, arsenic, mercury, zinc* and other metals may be looked for under corresponding conditions in the appropriate areas.

Near the seacoast ground waters may be contaminated with sea water, although it not infrequently happens that a source of fresh water, sometimes rising to a height above sea level, may be developed right at the shore line or on adjacent islands. The hydraulic conditions which control these situations and which have to deal with the serious problem of *salt water intrusion* into overworked deep wells near the sea coast have been somewhat extensively studied.

Ground Water Pollution. The chance of any serious residual pollution of ground waters from surface drainage, seepage from privies and cesspools, or other sources is greatly lessened by their slow movement and prolonged sojourn in the immense storage reservoirs of the underground water system. We deal elsewhere (chapter 12) with the pollution and self-purification of natural watercourses in general, including the ground water systems; also (chapter 16) with the relation between the pit privy and the well in close association under rural conditions. It suffices to point out here that the essential element in self-purification is the natural death rate which characterizes the pathogenic bacteria when exposed to the unfavorable environmental conditions of the stream. Given such a death rate, the mere lapse of time is sufficient to bring about any specified degree of self-purification. This feature, common to all waters, is augmented in the ground waters by extensive and long-continued filtration through the soil. Ground waters are, therefore, inherently purer than surface waters with respect to organic and bacterial pollution of the more objectionable kinds.

THE FORT CASWELL STUDIES. An important series of studies, carried out by the U. S. Public Health Service at Fort Caswell, N. C.,* developed some important principles regarding the passage of pollution through a homogeneous sandy soil. Experimental pit privies were established in a remote and unpopulated area lying between a fresh water lake and the sea. The direction of the ground water flow was therefore known at all times, and the elevation and hydraulic gradient of the water table and other hydrologic features were readily established.

Test wells were installed along several radii extending outward in a fanlike pattern from each of the pits. At each sampling location wells were put down to three different depths. Pollution was measured and recorded in terms of a soluble blue dye added in quantity to the pits and also in terms of coliform organisms. Invariably the visual discoloration of the water by the dye preceded the appearance of coliforms at any given location.

Throughout the 2-year period of the experiment the lateral progress of the pollution through the soil was continuous. In one experiment the presence of coliforms indicated that it had passed through 232 feet of sand during a period of 32 months. It was still progressing, although at a very much reduced rate and concentration at the conclusion of the tests.

One of the most important findings of the study is illustrated in Figure 54. Let this represent, in the first instance, a river into which a sewer *S* is discharging. The tendency of the influent sewage is to travel downstream with a limited amount of lateral mixing. Such mixing as does occur is due to turbulence, eddying and crosscurrents set up by irregularities along the bottom and sides.

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* C. W. Stiles, H. R. Crohurst, and G. E. Thomson, *U. S. Pub. Health Service, Hyg. Lab. Bull.* 147, 1927.

As the figure is drawn, unpolluted water could be taken at the intake *I* downstream from the sewer outlet.*

Now let this plan view be turned up so that it represents a vertical cross section of the ground and the ground water. The line which represented the stream bank is now the water table. A pit privy penetrates the water table and drains into the ground water at *S*. In this situation, as was demonstrated by the Fort Caswell experiments, the stream of polluted water shows but little vertical and lateral mixing. It tends, rather, to flow as a distinct stream in the direction of the ground water movement and at or near the surface of the water table. The relative lack of vertical and lateral mixing is quite understandable if it be recalled that the slow ground water flow through a homogeneous soil formation is without turbulence, and, further, that there is nothing corresponding to the open channel of the river with relatively high velocity and bottom irregularities leading to eddying and crosscurrents.

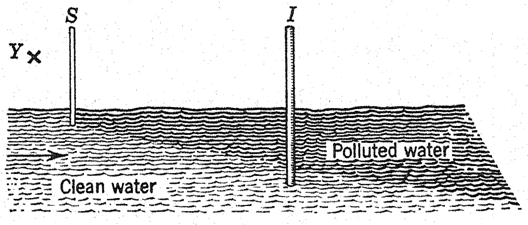

FIG. 54. Ground-water pollution by pit privy.

The pollution carried by the moving ground water tends to filter out in the capillary fringe when the water table declines during dry weather. Bacteria, thus stranded, with time, die out. However, with a subsequent rise in water table the survivors are again picked up by the moving ground water and carried forward. The dry periods of receding water table are, therefore, periods of greatest self-purification.

Normally, the ground waters outside the limits of a relatively narrow sector below the source of pollution are unaffected. There are

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* Such a practice is not to be recommended, but the illustration shows quite accurately the situation which existed for many years at Detroit, Mich. A quite satisfactory water was found in the swiftly flowing deep waters of the Detroit River well out and beyond the heavily polluted inshore waters.

important modifying factors, however, altering the normal flow of pollution, which are dealt with later.

The danger of direct discharge of pollution to the ground water by penetration of the water table and the relative safety of keeping the discharge pit *above* the water table were clearly disclosed by the Fort Caswell studies and the earlier work of Kligler.* This also can be demonstrated by the simple illustration of Figure 54. Pollution does not migrate of itself; it is moved from a focal point only by mechanical translation or is transported by fluid flow. Thus, if dry excreta were deposited on the surface of the ground at *y* (Figure 54) well above the bank of the river, inaccessible to man or beast, and, further, if it were protected from rain and drainage, the possibility of the pollution's reaching the river and being carried downstream would be very remote. Again, turn the figure up so that it represents a vertical cross section of the ground and the ground water. *y* now represents a pit privy receiving dry excreta, the bottom of which is well above the ground water level. In this situation the pollution is confined practically to the immediate vicinity of the pit with no contamination of the ground water. In similar tests, but with pits liberally dosed with water to simulate heavy rainfall, bacterial pollution was traced through the fine sand to a depth of 5 feet below the bottom of the pits. If excreta can be kept dry (nonfluid), isolated, and *above* the water table level, the danger of contamination of ground water is remote.

THE ANDALUSIA AND OTHER INVESTIGATIONS. The nature of the pollution of ground water in nonhomogeneous soil formations is no different in principle from that just described, except that the vertical and lateral distributions may take different paths, depending upon the varying course of ground water flow through differing strata. A noteworthy series of investigations, sponsored by the Rockefeller Foundation at the Field Research Laboratory of the Alabama State Department of Health at Andalusia,† confirms the results of the Fort Caswell studies and, in addition, indicates the importance of varying soil formation.

The flow of water follows the path of least resistance, which, in a nonhomogeneous soil formation, is through the strata of *greatest permeability*. Gravel and coarse sand have high permeability, whereas

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* I. J. Kligler, *Rockefeller Inst. Med. Research Monograph* **15**, October 10, 1921.

† E. L. Caldwell and L. W. Parr, *J. Infectious Diseases,* **61**, 148, 1937; E. L. Caldwell, *ibid.*, **61**, 270, 1937; **62**, 225, 272, 1938.

fine sand, silt, clay, and sand or gravel with interstices filled with silt or clay have low permeability. Further, the filtering action of soils varies inversely with permeability. Thus, pollution discharged into the ground water flow will travel farthest in highly permeable formations.

In nonhomogeneous soils, particularly if the water table level is subject to fluctuation, differences in permeability result in a meandering path of flow, with pollution distributed laterally over a wider belt than normally would be expected.

One of the most important findings of the Andalusia studies was the possibility of deep vertical penetration of pollution in certain nonhomogeneous formations. With a pit privy penetrating below the water table in a soil formation of marked vertical gradations in permeability, such as coarse sand and gravel beneath fine sand, the flow of pollution was observed to be downward, as well as outward, with pollution extending to depths substantially below the water table level.

The normal path of flow may also be altered by reduction of natural permeability through the filling of the soil interstices with end products of organic decomposition. This was observed* to take place after a period of operation, particularly with the pits extending below the water table sufficiently to provide fluid to insure septic action. This reduction in permeability, or clogging, is termed "defense," as it tends to reduce the distances to which pollution travels in the ground water. However, permeability may be reduced to such a degree that pits surcharge. Then a new level of hydraulic gradient establishes new paths of flow, other than in the direction of the natural water table slope; or the pits overflow at the surface of the ground.

THE ROCKVILLE CENTER STUDIES. A dramatic demonstration of the great protective capacity of the soil against bacterial pollution of the ground water is the evidence reported for the Rockville Center, Long Island, case.† The sewage of a population of 12,000, after activated sludge treatment, is returned entirely to the ground water through 5 acres of recharge beds. The soil is a relatively homogeneous fine sand formation and the natural ground water drainage is toward an outcropping spring, 1500 feet from the

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* E. L. Caldwell and L. W. Parr, *J. Infectious Diseases,* **61**, 148; 180, 1937.
B. R. Dyer, *Indian J. Med. Research,* **29**, 867, 1941; **33**, 23, 1945.

† A. F. Dappert, *Water Works & Sewerage,* **79**, 265, 1932.

recharge beds, at the head of a small creek. The effluent as applied to the recharge beds contained a high concentration of coliforms. A clearly defined path of pollution travel below the recharge beds was located by tests for chlorides. Bacteriological samples taken from a test well located in the line of flow, 400 feet below the beds, in no instance showed the presence of coliform in 10-milliliter portions. The exact extension of bacterial pollution was not determined, as test wells were not located closer than 400 feet. The fact that under such severe loading (1.2 million gallons per day) coliform extension was less than 400 feet emphasizes the great protective capacity of the soil against bacterial pollution of the ground water.

The Rockville Center studies brought out the fact, however, that, although the extension of bacterial pollution is limited, *chemical* pollution may extend substantial distances. Chlorides, nitrogen, and free ammonia were recovered at the spring, 1500 feet below the recharge beds. Such chemical pollution, although not harmful, may under certain conditions be quite objectionable in well water supplies. It can be concluded that where there is no evidence of chemical pollution it is practically certain there will be no dangerous bacterial pollution.

UNCERTAIN HISTORIES. Ground waters are frequently taken from seams in solid rock formations under circumstances which make it impossible to know whether they represent infiltration from an adjacent highly polluted fish pond or have their origin in a watershed many miles away. The deep wells so frequently relied upon for private supplies in the granitic region of Westchester County, New York, and Fairfield County, Conn., present many examples of this sort of uncertainty, and examples are not lacking of waters taken from the "solid rock," and thereby presumed to be of high degree of purity, showing upon investigation evidence of near-by and serious contamination.

In limestone regions the element of uncertainty is still greater. Underground rivers are often found in these rocks, fed through *sink holes,* into which drainage from the surrounding territory passes, and into which, at times, municipal sewers have been purposely run. Many of the ground waters of Florida are of this sort. Only a rather complete knowledge of the geology of the region will provide any clue to the actual history and possible sources of pollution.

The most satisfactory type of ground water is one taken from glacial deposit or other permeable formation below an impervious stratum of hardpan or clay and under such a static pressure that, when the well is developed, the water will rise above the ground surface, or at least above the level of the superficial ground waters. Such a situation generally indicates a remote and higher source and gives a considerable assurance of safety.

Where available, ground waters are often an excellent source of safe water. If properly developed, the natural protection against contamination makes it possible to utilize these waters without treatment. Whereas a relatively few great surface water systems serve large urban populations, the semiurban and rural communities are served by thousands of small ground water systems.

Because of the characteristic differences between surface and ground waters and also because distinctly different techniques are employed in their collection and conservation it will be advisable to deal separately with these two major sources of water supply.

COLLECTION AND STORAGE OF SURFACE WATERS

WATERSHED PROTECTION

The drainage area from which the surface waters flow to reach any given point, the *watershed* above that point, is determined by the topography of the land and the pattern of the river valleys. There is a corresponding area for ground waters, but it is not usually so well defined. It is generally referred to as the *intake, gathering,* or *recharge area.*

Protected and Unprotected Sources. Taking the surface water supplies of the United States as a whole, we find two distinct types of watershed with respect to their sanitary protection, with little or no intermediate gradation. The first of these is exemplified in the Ohio River, into which the sewage of each community is discharged without treatment, and from which each in turn draws its water supply. The other type is represented by the water supply of many cities along both East and West Coasts, where an attempt is made to develop and protect the surface waters of a certain watershed and to maintain them in as high a degree of purity as is economically feasible. In the former case, reliance is placed wholly upon the potentialities of water purification (natural and artificial); in the latter, watershed protection plays a principal role.

Complete Control. An extreme example of a protected area is one in which the entire watershed is under control and restricted to its single function. This is possible only in the case of communities utilizing a watershed originally sparsely inhabited and of low market value for agricultural or other uses. The city of Newark, N. J., adopted this procedure in certain of its important collecting areas. Where highways traverse the area, a system of patrolling is necessary, and in this particular instance the difficulty of controlling picnic parties is solved by the definite provision of areas set aside for this purpose, provided with fireplaces, tables, and sanitary facilities.

Partial Control. A more moderate and typical example is the plan adopted by the City of New York. The drainage area of its Croton supply is well populated, and contains many communities of considerable size. The city, by legislative authority, has sanitary jurisdiction over this area, and may, at its own expense, divert town sewage out of the watershed or install adequate purification works. In the rural sections, supervision is exercised to the extent of procuring reasonably safe treatment of household wastes, and considerable areas of land adjacent to the collecting reservoirs are owned and controlled.

Watershed control of this sort depends primarily upon complete and detailed knowledge concerning all possible sources of pollution and regular sanitary inspections to assure proper functioning of established control measures. At best these supposedly protected watersheds differ from those along the Ohio River only in degree. It would be futile to hope for anything approaching perfection in watershed control measures. Safety lies in the frank recognition of the continual possibility of a definite degree of pollution and in the provision of appropriate safeguards.

The Principle of Multiple Barriers. Nevertheless, a protected or originally pure water is unquestionably superior to one that is continuously and extensively polluted. This thought was well expressed at one time by a leading sanitary engineer of his day, the late Rudolph Hering, when he said, concerning water supply sources, "Innocence is better than repentence."

It might reasonably be asked, if adequate means of water purification are available and employed, why undertake watershed protection? The answer involves a principle which may well be considered in its broader public health aspects. It might be termed the *principle of multiple barriers*. It recognizes as axiomatic the fact that all human efforts, no matter how well conceived or conscientiously applied, are imperfect and fallible. Control measures, whether they be applied to the watershed, the dairy farm, or the mosquito-breeding swamp, cannot guarantee complete protection, and treatment processes such as water filtration and milk pasteurization have their good and bad days and are subject to occasional lapses and breakdowns. Regarding each protective device as a barrier against the passage of disease, the ideal system is one involving all known devices, arranged as a series of barriers and so planned that the temporary failure of any one would not endanger the health of the consumer.

It is quite true that the water of a heavily polluted stream may be treated and made to serve as a domestic water supply, but a similar treatment applied to a protected or less polluted water possesses a greater margin of safety and a decreased likelihood of an unfavorable reaction upon the consumer in case of partial failure. The water treatment processes themselves are made up of a series of barriers, and in many other fields of public health and environmental sanitation, the principle of multiple barriers is employed for greater safety.

WATER STORAGE: QUANTITATIVE REQUIREMENTS

THE PURPOSE OF STORAGE. If a body of water, such as one of the Great Lakes or the Mississippi River, has at all times a sufficient volume or flow to provide for the demands of a city, the problem of collection is reduced to the provision of such engineering structures as intake works and pumping plant equipment. On rivers like the Ohio, where there is a wide range in surface elevation of the stream during the year, there are problems of locating these works, and especially of protecting them against flood conditions, but these are readily solved.

At the opposite extreme, the small upland streams that supply many of the cities of the Eastern Seaboard are often utilized nearly to the extent of their total annual volume. The stream flow or *runoff* is usually maximum during the early spring thaws and may recede to very low values in the late fall of a dry year.

Not all of the yearly flow of such streams can be depended upon for direct diversion to meet the demands of public water supply. During the flood stages the yield is in excess of needs, and much of the flow is lost down the river; whereas during low water stages the flow is less than the requirements. *Storage* is the process of saving the excess of flood flows; of adjusting a variable supply to a nearly constant demand. The greater the variation in flow, the greater is the need for storage.

There are several methods in use for computing storage requirements. The most reliable results are obtained from methods which employ hydrological principles and the statistical method. The particular method used will depend upon the data available and the degree of accuracy required in the project.

THE MASS DIAGRAM. The basis of all these methods is the mass diagram, frequently referred to as the Ripple diagram. There is first plotted a summation curve of accumulated stream flow against time —the wavelike curve in Figure 55. The slope of the curve at any point represents the runoff at that time. Where the slope is steep, the runoff is high; where it is flat, the runoff is low.

From the origin at *O* construct a similar summation curve of the constant mean daily demand—the line *OF*. Where this is steeper than the runoff curve, demand exceeds runoff and storage is required; where it is flatter, supply exceeds demand and water is accumulated in storage or wasted.

By superimposing lines parallel to line *OF* upon the runoff curve at points *A, D, E,* etc., where the two are tangent, three areas are developed as indicated; these are the quantities: (*a*) supplied from current stream flow, (*b*) drawn from storage, and (*c*) wasted during periods of maximum flow.

The maximum vertical distance *S* during the period when there is a draft on storage, represents the net storage required to insure the continuous daily demand over that period.

ESTIMATING REQUIRED STORAGE. In the short mass diagram method of estimating required storage, the diagram is merely inspected for the most severe seasonal drought period, which is the period developing a maximum value of the storage line *S*. This value is taken as the required storage (second year in the diagram).

In the long mass diagram or statistical method values of required storage *S* are determined for each year of the record. These values form a statistical series which may be plotted on probability paper or analyzed by standard statistical procedures for the determination of the mean value and its standard deviation and coefficient of variation. Either procedure provides a means for the determination of the extent of the drought period (and corresponding storage required) which has an expected return period of any given number of years. A generalized statistical method, based upon annual runoff data, is available which avoids the labor of plotting the mass diagram.*

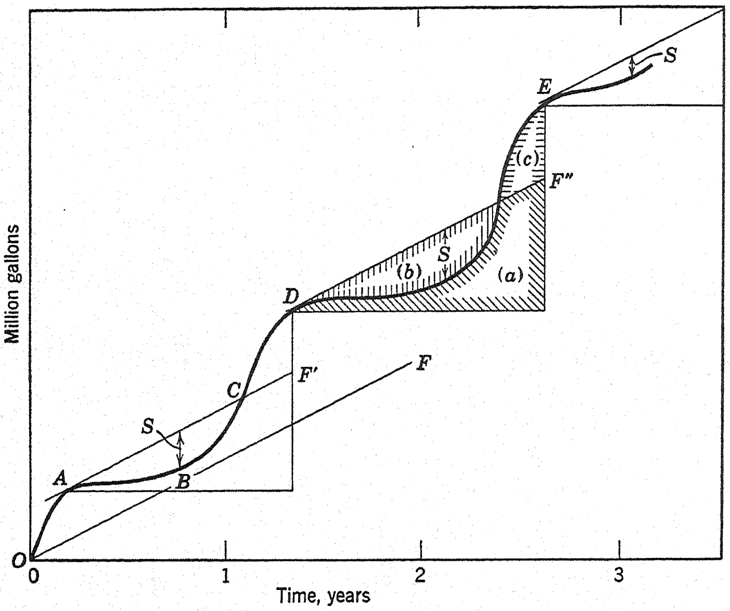

FIG. 55. The mass diagram.

Line *O-A-B-C-D-E*	Summation of accumulated stream flow.
O-F	Summation of daily demand.
A-F′, *D-F″*, etc.	Demand lines parallel to *O-F*.
Area (*a*)	Supplied from current stream flow.
(*b*)	Supplied from storage.
(*c*)	Wasted.
A	Decreasing stream flow just equals demand.
A to *B*	Reservoir being depleted.
B	Maximum depletion *S*.
B to *C*	Reservoir filling.
C	Reservoir full.
C to *D*	Reservoir overflowing.
D	As at *A*.

For practical design of water supply, provision for the drought having an expected return period of 20 years is considered sufficient insurance against deficiency in the supply. However, other chances

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* Allen Hazen, *Trans. ASCE, 77*, 1539.

of falling below the demand can be taken, and such risks are balanced against the cost of providing the required storage.

CORRECTED OR GROSS STORAGE REQUIREMENTS. The values computed by any of the foregoing procedures are *net storages* and, in practice, must be corrected for the following items:

1. Evaporation from the surface of the proposed reservoir.
2. Dead storage below desirable drawdown elevation in the reservoir.
3. Seepage losses to the stream below the dam.
4. Soil storage; water stored in the ground about the reservoir which will be released as seepage into the reservoir at low stages.
5. Any minimum stream flow that may be required below the dam must be added to the water supply demand before the storage is computed.

The short method of computation provides no measure of the *probability* of future occurrence of periods of a similar or greater degree of drought. Hence the long method is preferable wherever the problem warrants and the data justify it.

Many empirical methods have been developed for converting rainfall records into runoff in an effort to augment meager stream flow data. Also, long records from other similar catchment areas are utilized to extend the short record for the drainage area in question. An average ratio between the long and short records is established during the period for which data are available for both streams, and this ratio is applied directly to the long record to obtain an extension of the short record. Such methods are obviously crude and limited in application and are not to be encouraged. A rational approach to augmenting meager runoff records is afforded in Meyer's method of computing "Precipitation Minus Losses" (chapter 9).

EFFECT OF STORAGE UPON QUALITY

FAVORABLE EFFECTS. The quality of stored water is modified in several ways by storage. Favorable changes are removal of turbidity by sedimentation and of color by the bleaching action of the sun. Early studies of color removal in the reservoirs about Boston showed that it progressed with time and was more conspicuous in the upper levels and at times of maximum solar energy. Weston has summarized his own extensive observations as follows:*

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* R. S. Weston, *J. Am. Water Works Assoc.*, **31**, 1805, 1939.

Storage Days	Color Reduction, Per Cent
50	19
100	27
150	33
200	38
250	42
300	46
350	50
400	53
450	56
500	60

The most significant change in quality brought about by storage is that due to the natural death rate of bacteria, especially the bacteria of sewage origin, when exposed to the unfavorable environmental conditions of a stream. This is dealt with in the discussion of the self-purification of streams in general (p. 397).

Unfavorable Changes. Tastes and odors quite frequently develop in storage reservoirs as a result of the growth of micro-organisms. These growths are conditioned largely by food supply. They are most likely to cause trouble in newly constructed reservoirs, and especially so if the original reservoir bottom was marsh or swampland. Complete removal of the rich organic topsoil over the reservoir area, *stripping,* was practiced in some of the earlier Massachusetts reservoirs, but the present tendency appears to be to rely almost wholly upon the process of aging. Within a few years, this completes the decomposition of the organic matter upon an ordinary clean reservoir bottom. Swampy areas are either covered with sand or preferably diked off. Areas of shallow flow, that are alternately exposed and covered will develop growths of weeds which subsequently decay, producing odor and taste in the water and organic food for micro-organisms. Such areas are likewise removed from the general circulation by dikes.

Storage reservoirs are especially vulnerable near their lower or outlet ends; pollution entering the waters there goes directly to the system without any of the benefits of storage. For this reason among others, local drainage from this area should be especially protected or preferably diverted.

The limited use of storage reservoirs for recreational purposes has its pros and cons. Reservoirs are usually well stocked with fish, and it is probably better to keep this stock reduced by well-controlled fishing. Special permits may be issued to responsible persons who are fully advised of the necessary sanitary precautions; the permit to be revoked for any violation. Bathing is usually prohibited in controlled reservoirs and would appear to be undesirable in the streams above them. This, however, is purely a relative matter, and under the circumstances that prevail in so many places where sources are extensively polluted in other ways and where reliance is placed upon purification treatment, the use of the streams for bathing has less significance and has its place in multiple water use.

THE DEVELOPMENT AND UTILIZATION OF GROUND WATERS

TYPES OF WELLS

A well is a means of access to an underlying body of ground water. A *dug well* is usually 3 or more feet in diameter lined with some sort of masonry; loose stone, cemented brick or stone, tile or concrete.

A *driven well* is constructed by driving a pipe (the *well casing*), tipped with a *well point* down to the water-bearing stratum. It can be driven only through permeable soft material which becomes tightly compressed along the sides of the casing.

A *drilled well* is one constructed through hardpan or rock by actually drilling out the material through which it passes. It may later be lined through the whole or a part of its length by a driven casing. Both driven and drilled wells may pass through an overlying water-bearing stratum, or *aquifer,* to a lower and more suitable one, in such a manner that the casing seals out the upper undesirable water.

QUANTITATIVE YIELD OF WELLS

DEFINITIONS. The deep underground water strata overlain with impervious formations are usually under pressure. If such a stratum is tapped by a drilled well, the water will rise above its confining impervious ceiling to a level in equilibrium with the pressure of the atmosphere (see Figure 56). This level is referred to as the normal piezometric surface. If water is pumped from the well, the level will drop to a new equilibrium with each given rate of pumping. This drop in the normal piezometric surface is the *drawdown D*.

If a series of tubes penetrating the water-bearing stratum are placed radially surrounding the well, it may be observed that during pumping the water level in the surrounding tubes will likewise be lowered, greatest in those near the well and decreasing along a curve, approaching the normal piezometric surface as the distance from the well increases. This pattern of lowering of the normal piezometric surface surrounding the well is the *cone of depression*. The outer limit of the cone of depression, where it meets the normal piezometric surface, measured radially from the center of the well is the *radius of the circle of influence R*.

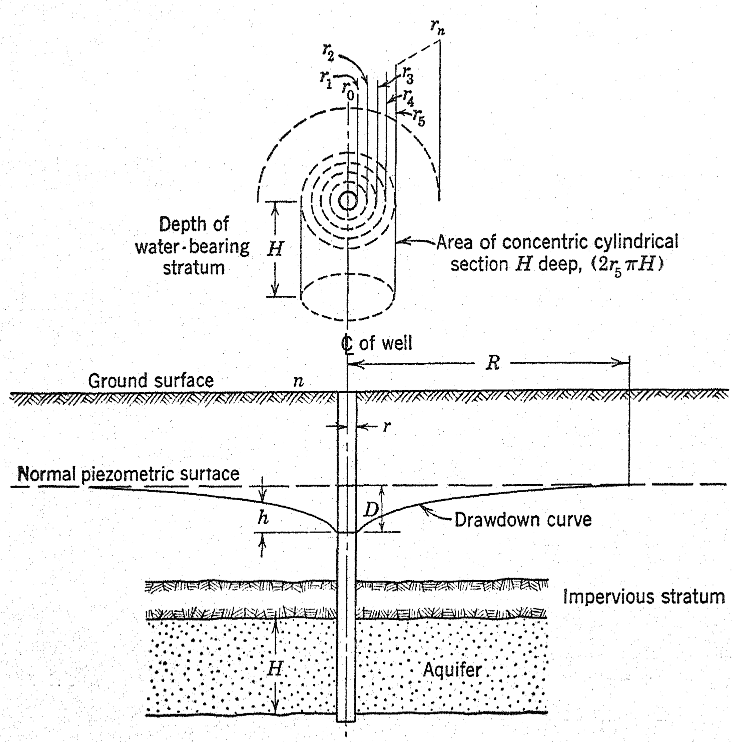

FIG. 56. Plan and sectional view of deep well.

During pumping the rate of flow or *yield* of the well is closely proportional to the drawdown. From this relation the *specific yield* of the well is defined. It is the rate of flow per unit drawdown (usually expressed as gallons per minute per foot of drawdown). Thus, if a well yields 100 gallons per minute at a 10-foot drawdown, its specific yield is 10 gallons per minute per foot of drawdown. From the specific yield, the delivery of the well at any other drawdown may be approximated.

DETERMINATION OF THE SPECIFIC YIELD. The specific yield increases with the well diameter. It also depends upon the characteristics of the aquifer, particularly its porosity. Thus no generalization of quantitative yield from different aquifers is possible. The specific productive characteristics must be determined in the first instance by performance of test wells. If these characteristics are known, estimation of yield and associated features of drawdown and cone of depression can be made by application of hydraulic principles.

Churchill's *unit-head-loss* method* offers a simplified approach to the hydraulics of deep aquifers, which is a convenient aid in the solution of practical problems of flow of water from wells.

Water flows in response to a difference in hydrostatic pressure or head. This difference, the head loss, may be recognized as a difference in elevation of the free surface (in an open channel), or as a difference in pressure (in a closed pipe). Part of the energy represented by the head loss becomes energy of motion; but, in view of the slow rate of movement of ground water through the interstices of the aquifer, it may be assumed in this case, without serious error, that the entire head loss represents work done in overcoming frictional resistance to the flow.

This resistance, in turn, is a function of the soil texture (porosity and grain size and shape) and of water viscosity. In particular (again at the low velocities under consideration) it is directly proportional to the velocity of flow. The *hydraulic gradient,* as measured over any finite distance, is the head loss per unit distance. In dealing with a gradient variable with distance, it is more conveniently defined by the differential,

$$dh/dx$$

Figure 56 represents a well penetrating an aquifer through its depth. The drawdown, radius of influence, and both normal and operating piezometric surfaces are indicated. For simplification, it

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* M. A. Churchill, *Civil Eng.*, **10**, 307, 1940.

may be assumed that the characteristics of the aquifer, including its thickness, are constant throughout and that the water flows radially toward the well in horizontal lines. The lines of equal head are, therefore, concentric circles about the well center.

The areas of the successive concentric cylindrical surfaces increase directly as the radial distance, and, since the flow of water passing each such surface is the same, the respective velocities are inversely as the distance. Finally, the hydraulic gradient, being proportional to the velocity, is itself inversely as the distance, or

$$dh/dx = \frac{a}{x}$$

a being an arbitrary constant combining the various proportionality constants introduced.

Expressing distances in terms of the well radius, integrating between the limits $x = 1$ (the well wall) and $x = n$, and transforming to common logs for convenience, we have

$$h = 2.3a \cdot \log n \qquad (1)$$

Churchill's unit-head-loss U is the loss through the ring immediately surrounding the well wall and of one radius thickness, that is, between $n = 1$ and $n = 2$, and hence, has the value,

$$U = 2.3a \cdot \log 2 = 0.692a$$

The constant U is a characteristic of the aquifer. The constant a may be determined by noting the elevation in any conveniently located test hole and through the general relation (1). The elevation (h in the diagram) of the piezometric surface, above the drawdown level in the well itself, in terms of the unit head loss U, is

$$h = \frac{2.3aU \cdot \log n}{0.692a} = 3.322U \cdot \log n \qquad (2)$$

n being the distance in well radii of any test hole from the well center. This is the general equation of the drawdown curve.

Graphical Solution and Examples. Figure 57 provides a graphical solution of this relation. From it one determines:

1. The value of the unit-head-loss U by comparison of the drawdown in the well and in a test hole distant n radii from the well center.

2. The drawdown at any other point within the circle of influence.
3. The radius R of the circle of influence.*
4. The corresponding characteristics of a well of another diameter of bore.

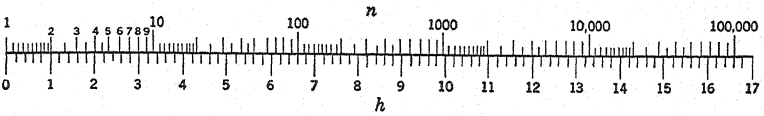

FIG. 57. $h = 3.322 \log n$.

Two examples will illustrate this procedure:

1. *Given*: Well diameter, 12 inches; drawdown, at 500 gallons per minute, 50 feet in well and 10 feet in a test hole 100 feet from the well.

Find: The radius of the circle of influence R; the drop in the normal piezometric surface at a point 200 feet distant from the well.

Solution:

From (2), or Figure 57, the value of h at 100 feet (200 radii) is 7.65 U. The actual value as measured is $50 - 10 = 40$ feet.

Hence
$$U = \frac{50 - 10}{7.65} = 5.23 \text{ feet}$$

Since the drawdown at the well, 50 feet, is the total head loss out to R,

$$50 = 3.322\, U \log R$$

whence

$$R = 756 \text{ radii or } 378 \text{ feet}$$

---

* It may be noted that constant drawdown (at a fixed rate of pumping) and a limited circle of influence are merely convenient practical concepts. With an initially horizontal piezometric surface (no normal ground water movement) a steady state will never be reached; water must enter any assigned circle of influence from without that circle to avoid eventual depletion within. Hence, there will be a gradually increasing drawdown and widening circle of influence. These eventually reach nearly constant values, and usually there is an initial gradient in the normal piezometric surface indicating ground water movement. This, together with other conditions eliminated in our simplifying assumptions provides a certain inflow and tends to limit the circle of influence.

At the point 200 feet distant (400 radii),

$$h = 3.322 \times 5.23 \times \log 400 = 45.2$$

$$\text{Drawdown} = 50.0 - 45.2 = 4.8 \text{ feet}$$

2. What would be the drawdown if the 12-inch well is replaced by one of 24 inches?

Solution:

Since U is a characteristic of the aquifer only, it is sufficient to determine the elevation of the water surface under the conditions of example (1), at 12 inches (two radii) from the center. This is (by definition) exactly U or 5.23 feet above the original drawdown level. Hence, the new well will be drawn down

$$50 - 5.23 = 44.77 \text{ feet}$$

In general, doubling the diameter decreases the drawdown by one unit-head-loss U; and, by reverse reasoning, halving the radius increases it by U.

WELL CONSTRUCTION AND SANITARY PROTECTION

Water-Bearing Strata. The nature and location of the water-bearing strata which the well is intended to reach determine to a large extent the type of well construction to be employed and the provisions made for its protection. Beneath any given location there may be several aquifers differing from one another in hydraulic characteristics and independently supplied with waters of differing chemical composition and under differing pressures or heads. These will be found at different depths and, if truly independent, will be separated by impervious strata.

The Upper Ground Water or Phreatic Water. This formation is almost universally present. It comes from the drainage of the immediate area and is stored in an aquifer which is usually homogeneous or at least continuous with the surface stratum. It develops a definite water table at which it is under atmospheric pressure. Below the water table it is under hydrostatic pressure and will flow into a well; hence *phreatic* water.

It has been shown (p. 342) that the uppermost surface of this water carries the majority of the pollution of the immediate drainage area modified by whatever protection is afforded by filtration and the lapse of time between the source of pollution and the point of withdrawal.

A minimum requirement for protection is a tightly constructed wall extending well below the extreme low water line of the fluctuating water table. In a dug well this means a cemented or concrete wall. Sections of precast concrete pipe, lowered into place by undermining and cemented at the joints, make a suitable well structure.

Driven or drilled wells require that the soil be tightly compacted about the casing which extends well below the water table. Any well which *runs dry* during drought is not protected against the polluted surface drainage of the immediate area.

THE DEEPER AQUIFER. In many locations a more desirable supply may be found in one of the deeper aquifers. The advantage may lie in quality, available quantity, continuous reliability, or pressure. The last is a unique characteristic of the deeper waters, which, when tapped, frequently rise to an elevation above that of the normal water table of the phreatic water and, in many cases, above the ground level itself (artesian flow).

Under any such pressure relations there is no problem of protecting the waters of the lower aquifer against pollution from above; the natural flow is in the other direction. If however the hydrostatic pressure of the supply under development is lower than that of any overlying waters, then the same problem arises as in the development of the phreatic water. Casings passing through waters that are to be excluded must be tightly driven into the hardpan, clay, or impervious rock stratum that underlies those waters and separates them from those below. Where two or more such aquifers are to be *cased out,* separate concentric casings of diminishing diameters are used.

TESTING WELLS FOR TIGHTNESS. The *dye test* provides an excellent test for the tightness of well walls and casings. Some such powerful dye as *uranine** is added to a surface excavation about the well wall. The well is then pumped continuously for several hours or a day, returning enough water to the excavation to keep it filled. Any direct leakage to the water table will be indicated by the passage of the dye.

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* Uranine is the commercial name of one of the fluorescent dyes. It can be detected in the laboratory in a dilution of one part per billion and has the valuable property of not dyeing organic soil material so that its strength is not wasted. It is most readily detected in the water, not by color, but by its fluorescence when viewed against a dark background.

DISTRIBUTION

Having provided an adequate supply of water for the use of the community, our next logical step would be to inquire into its quality and to consider what further treatment, if any, may be required to make it safe and acceptable at all times. The subject of water treatment, however, is so intimately associated with all three segments of the water contact cycle that its detailed consideration may well be deferred (chapter 14).

After the water has been suitably prepared at the treatment plant, it is ready for distribution to the consumer. The distribution system comprises the network of mains and pipes within the city or town itself together with distribution storage tanks or reservoirs and any necessary pumping arrangements.

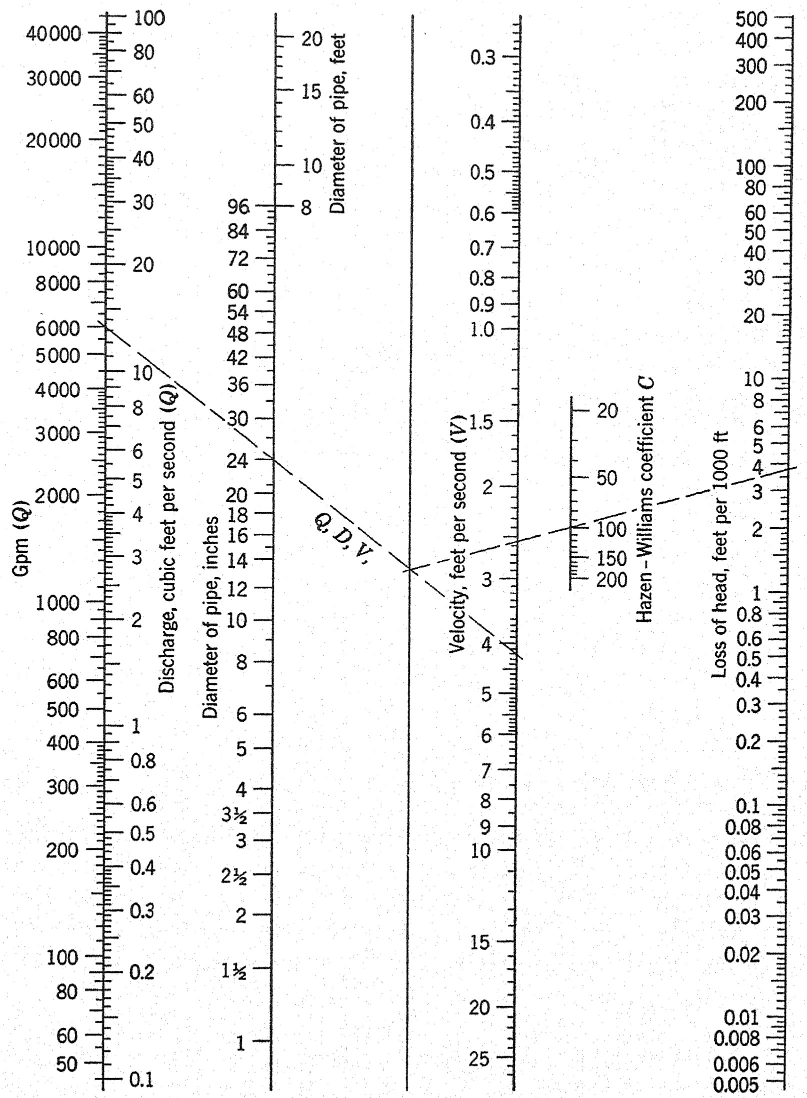
Types of Distribution Systems. We distinguish *gravity, pumping,* or *combination* distribution systems according to the means employed to provide the necessary *head* or *pressure*. A system relying wholly upon gravity is possible if the source and the major storage reservoirs are located at sufficient elevation above the city datum to provide adequate pressure throughout the city. In rare instances artesian ground water sources will provide the necessary pressure, but, in general, ground waters and waters taken from near-by lakes and streams require pumping.

Gravity systems are to be preferred because of their reliability. Under most circumstances they are also more economical in operation although this feature may be somewhat offset by a larger capital investment. A combined gravity and pumping system is illustrated in Figure 51 (p. 331).

THE PIPE NETWORK

The pipe network, required to distribute the supply, consists of feeder and service mains, house services, valves and hydrants. Figure 58 is a nomographic chart which will be found convenient in the hydraulic analysis of distribution networks.

Feeder and Service Mains. The feeder mains form an interconnected network or grid, spaced at about 2000-foot intervals and circumscribing the entire community. This grid forms the backbone of the distribution system, carrying water to the various areas of the city. It should be a system of closed circuits with no pro-



Courtesy of Thomas R. Camp

Fig. 58. Alignment chart for flow in pipes.

Hazen–Williams Formula: $V = 1.318\, CR^{0.63}S^{0.54}$

truding *dead ends*. Water from dead ends is likely to be colored from pipe corrosion and to give rise to complaints of *red water* or to develop musty odors. Within, and connected to each feeder circuit, are the service mains, following the pattern of the street system. They likewise should be without dead ends and should provide free circulation in each direction. The service mains (6-inch to 8-inch) are tapped for the house services.

The feeder and service mains are laid approximately parallel with the street surface and at a depth of at least 3 feet for protection against breakage from traffic. Where the winters are severe, the depth is increased to below frost penetration which may vary from 4 to 8 feet.

Valves and Hydrants. Valves are placed at intersections of mains in sufficient number to insure large areas from loss of service in the event of a break in a main or during repair operations. Usually three valves are placed at crosses and two valves at tees.

Hydrants are located at the curb line near intersections. The number and spacing depend upon the number of fire streams which are potentially required to protect the types of structure in each particular area. Spacing will range from 150 feet to 300 feet. Where fire hose is directly connected to hydrants, not over 200 feet of hose should be required from any hydrant to any fire location.

The pressure carried in the distribution system depends to a large extent upon the type of fire-fighting equipment used. If fire hose is directly connected to hydrants, the pressure in the distribution system will usually require 75 to 100 pounds per square inch to insure a positive residual pressure in the pipe system during maximum fire draft. If mobile fire pumps are used, the pressure in the system can be reduced to 40 to 60 pounds per square inch. A positive pressure should be maintained in the distribution system at all times to protect against back siphonage from the household plumbing (see p. 375).

DISTRIBUTION STORAGE

It has been noted that the function of storage is to smooth out the normal irregularities of supply so as to meet the fairly uniform needs of demand. In this sense storage looks to seasonal and long-time variations.

Function. Distribution storage has an opposite function. The capacity of a long aqueduct or of a pumping station is fixed within rather narrow limits. This uniform hourly or daily capacity represents the most economical service which the system can render. As against this, the demands vary from hour to hour over a wide range and show some variation from day to day (see p. 336). There are also the extreme demands of fire service.

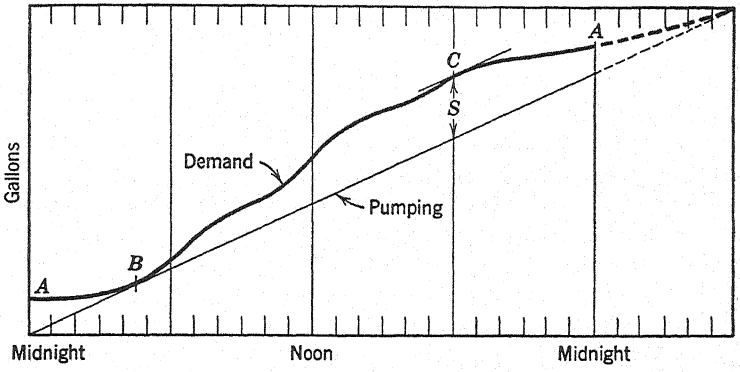


Fig. 59. Mass diagram of hourly demand, pumping and distribution storage. 24-hour pumping.

A to *B*	Refilling.
B	Full.
B to *C*	Draft exceeds supply; emptying.
C	Lowest point.
C to *A*	Refilling.
S	Storage.

It is desirable, therefore, to provide within the city or near it some distribution storage to be drawn upon when demand exceeds the economical rate of supply and to be refilled at night or during other periods of subnormal demands.

Storage Capacity. The quantity of storage required to meet the hourly fluctuations in demand can be obtained from a mass diagram of the 24-hour consumption on the maximum day. With a gravity system or with pumps and supply lines designed for a continuous and uniform rate of flow, the balance between supply and demand over a 24-hour period is shown in Figure 59. For pump operation over 12 hours of each day, the relations are indicated in Figure 60. Generally, with uniform 24-hour delivery, the storage required will amount to about 15 or 20 per cent, and with 12-hour operation, about 50 to 60 per cent, of the daily demand.

The quantity to be held in reserve for a major fire will vary with the size of the community from 5 to 10 hours of the maximum fire demand (see formula, p. 337). A city of 40,000, for example would provide for a 10-hour fire at 6000 gallons per minute or about 3.6 million gallons.

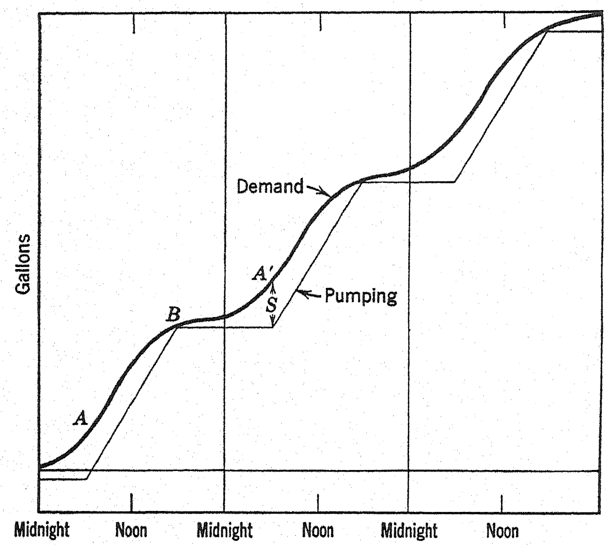


FIG. 60. Mass diagram of hourly demand, pumping and distribution storage. 12-hour pumping.

A	Lowest point; pumps start.
A to *B*	Filling.
B	Full; pumps stop.
A′	Same as *A*.
S	Storage.

The quantity to be held on emergency reserve for a major disaster to the water supply system, such as a devastating flood, will depend upon the vulnerability of the system. If, for example, the single supply main to the city crosses a river, danger of disruption by floods must be considered. It might require several days to make temporary repairs and a 5-day storage might be justified. On the other hand, if more than one supply line serves the city and the lines are not exposed to damage, the emergency storage may be substantially reduced. The National Board of Fire Underwriters advises an emergency storage equal to 5 days of maximum demand, but a more common quantity is 1 day's normal demand.

The total quantity of distribution storage is usually divided among two or more storage reservoirs, stand pipes, or elevated tanks, so located as to be near areas of maximum consumption. Location of distribution storage is dictated by topography, as natural elevation will often eliminate the necessity for standpipes and elevated tanks.

DISTRIBUTION PUMPING

Capacity. The capacity of the pumping system depends upon the distribution storage provided and the plan of operation. In large communities pumps are operated for 24 hours per day, whereas in smaller places they may be operated on only two 8-hour shifts or one 12-hour shift.

Obviously a 12-hour operation requires twice as much pumping capacity as a 24-hour schedule. The plan to be adopted depends upon a balancing of such factors as operating costs and labor, against equipment costs and costs of providing storage. The total pumping capacity is preferably divided among two or more units with some stand-by capacity for emergency and repairs.

Types of Pumps. Centrifugal pumps are small and compact in relation to their capacity, but are limited as to load variation. The older piston or plunger-type pumps are large and clumsy but more flexible as to speed and output. Air lift pumps are frequently employed in connection with wells.

The choice between steam and electricity as a prime mover depends upon economic analysis. Electricity is preferable for semiautomatic operation. Gas engines are seldom used because of cost of operation and unreliability. Diesel engines are economical but require skilled operation.

PUBLIC HEALTH HAZARDS OF DISTRIBUTION SYSTEMS

Throughout the various steps of collection, watershed protection, storage, and treatment of the water for domestic use, a major objective has been the delivery to the consumer of a safe water. Unfortunately, but not uncommonly, when all this has been done and when the laboratory examinations of the water, as it is sent on its way to the city, are most satisfactory, later examinations of samples from parts of the distribution system give evidence of pollution.

More detailed studies of situations of this sort will often show that there are many opportunities for reinfection within the distribution system itself, possibilities that are the more dangerous because of the assurance of safety that appears to reside in the favorable reports upon the water as it left the treatment works or reservoir. The principal public health hazards that are peculiar to the distribution system are (*a*) uncovered distribution reservoirs; (*b*) cross connections with auxiliary supplies; and (*c*) contamination of mains during repair, replacement, or extension. We reserve for later discussion a fourth type of hazard, back siphonage, associated more directly with the household plumbing system (p. 375).

UNCOVERED DISTRIBUTION RESERVOIRS

An open reservoir within the city limits, often a part of the scenic background of a public park, is always a minor hazard. It seems to be a natural human reaction to throw things into water. Whether this be an instinctive appreciation of the fact that, in nature, watercourses cleanse the land and constitute the final repository for the wastes of life is an interesting query. As a very practical matter, however, peanut shells, banana skins, and miscellaneous trash of a more or less objectionable character are usually disposed of by the water carriage system, whether into a mountain brook or a city reservoir. The excreta of domestic animals, cats, and dogs, and, where shrubbery provides convenient privacy, even human excreta, are deposited on the shores to be washed into the reservoir.

As a minimum protective measure, therefore, open city reservoirs should be well fenced, and all access to their immediate shore line, as well as to the bordering area that drains directly to the water, should be prevented. Even with the best of protection, reservoirs in cities usually collect sufficient wind-blown debris, dust from city streets, and other impurities to provide bacterial evidence of contamination.

Sea Gulls. A somewhat more serious situation developed in New York City some years ago which was traced to the presence of sea gulls in the area during the cold-weather months. It is the habit of these birds to spend the greater part of their time in the grossly polluted inshore waters about the city, feeding at the mouths of the city sewers. Between meals many of them resort to one of the city reservoirs for a cleansing bath.

Three of these gulls, taken while swimming in the city reservoir, were soaked in sterile water for a few minutes with a gentle hand massage. They yielded estimated numbers of coliforms ranging from 750 to 750,000 per gull, with a logarithmic mean of 15,000. Two gulls from the polluted waters of East River gave, on similar treatment, 2.4 and 31 million organisms per gull, respectively. It may reasonably be concluded that the differences represent the effect of washing in the reservoir after feeding in the river. The data are admittedly scant but, on their face value, indicate that one gull, making one trip from the river to the reservoir, might pollute between 100,000 and 1,000,000 gallons of water to the limit of the U. S. Public Health Service standard.* Under these circumstances, the significance of a coliform organism in the reservoir water as an indicator of dangerous pollution can hardly be overestimated. Largely because of these conditions, chlorination of the water as it leaves the reservoir was instituted. As a means of safeguarding waters held in distribution reservoirs within the city, this procedure has much to recommend it.

CROSS CONNECTIONS

Many industrial establishments maintain a private water supply for various purposes. An auxiliary fire supply providing water, when needed, through high-pressure fire pumps is a common example. Textile mills and paper mills use large volumes of *process water,* usually taken directly from a stream and perhaps treated for improvement in color, turbidity, or hardness, but with no attempt at hygienic improvement. Refrigeration plants at breweries, large milk-handling depots, and elsewhere require cool condenser water which is frequently obtained from deep wells of questionable sanitary quality.

A *backflow* as defined by the American Standards Association is a flow into the distribution pipes of a potable supply of water from any source or sources other than its intended source.

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* This experiment was suggested by Sol Pincus, Deputy Commissioner, New York City Health Department, and the laboratory study was made by Professor M. L. Isaacs of the School of Public Health, Columbia University.

An *interconnection* has, in the past, meant an arrangement whereby backflow may occur from a *drainage* system (see under plumbing). It is so defined in the New York State Sanitary Code. More recently, the American Standards Association has defined an interconnection as

> Any physical connection or arrangement of pipes between two otherwise separate building water-supply systems whereby water may flow, depending upon the pressure differential between the two systems.

When such a connection occurs between the main supply lines, however, as distinguished from the smaller piping of the interior plumbing system, it is better known as a *cross connection.*

FIRE PROTECTION SERVICES. Interconnections are frequently found as a part of the special fire protection service. Automatic sprinkler systems and a system of vertical piping of large dimensions with fire hose outlets at each floor are standard equipment in factories and in other large buildings. The entire system is normally kept under pressure by connection with the city water supply or other potable source used throughout the building. This provides for quick emergency use. At the beginning of any such use the engine room is warned by lowered pressure or other automatic arrangement, and the fire pumps are started to maintain an adequate fire-fighting pressure. The water for this purpose may come from a storage reservoir, a near-by stream, or other nonpotable and generally unprotected source.

During this emergency and, in fact, during the frequent tests that are called for to keep the fire-fighting system in a ready condition, a reverse flow from the fire system, now at higher pressure than that maintained in the city system, would occur in the absence of some protective device. Such a device is the *check valve,* which permits an unobstructed flow in one direction, but closes when the pressure is sufficiently increased from the opposite direction to induce a backflow.

Failures of check valves have been so frequently observed, and at times have led to such serious pollution of the domestic water supply of the community that interconnections of this sort are usually forbidden in state and city codes. Complete separation by means of an elevated tank to maintain the initial stand-by pressure on the system is the best solution, the tank being supplied by an overhead connection with the city supply, if desired, since an adequate air gap may be maintained at that point. If direct connection with the city mains is required, a system of double check valves with appropriate arrangements for testing each of them for operative integrity is permissible.

Industrial Supplies. Auxiliary supplies of water are often extensively piped through industrial plants, and other pipe lines may carry chemical solutions and other special fluids used in the plant operations. Interconnections are all too frequently made, by accident or design, with these auxiliary systems in order to prime pumps, to add water to tanks and vats and for other reasons, or even for no reason at all.

Connections of this sort are to be avoided in principle and are generally prohibited. A useful expedient, employed in many plants for their own protection, and one which should be required in any situation where the piping system is at all complicated, is to paint each separate system with a distinguishing color. This makes accidental interconnections less likely or excusable and greatly simplifies the task of the inspector in checking the system.

The Rochester, N. Y., Experience. A striking example of the dangers residing in cross connections is to be found in the experience of the city of Rochester, N. Y., during December 1940. The full report of this episode* is deserving of careful study, particularly as it deals with the emergency measures that were instituted to protect the public against gross pollution which had gained access to the distribution system.

About 80 per cent of the city's population is supplied by water of excellent quality derived from lakes. There is, in addition, a municipally owned fire-fighting system, consisting of about 25 miles of distribution mains, high-pressure pumps, hydrants, and automatic sprinklers. Normally this system is also served by the lake supply but, in emergency, water may be taken directly from the polluted Genessee River.

Originally there had been some 15 valved connections between the two systems. Since 1926 such connections had been prohibited under the sanitary code, and all *known* connections had been *ordered* removed. Apparently this order had not been fully executed, for on December 11, 1940, workmen making some repairs opened and left open one of these old and forgotten valves.

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* E. Devendorf, *J. Am. Water Works Assoc.*, 33, 1334, 1941.

The pressure was immediately reduced in the fire system, and, when speeding up the small fire pumps failed to restore it, the large pumps were started, and eventually some 5,000,000 gallons of river water were forced into the distribution system of the potable supply before the trouble had been diagnosed and corrected.

Mains were flushed and chlorinated and the public warned to boil all water. It was not until 6 days later that tests indicated a return to normal conditions throughout the city. Some 30,000 people within the city (11 per cent of the population supplied by this system) became ill with gastroenteritis; in addition, there were 3400 cases in the surrounding county, presumably employed or doing business in the city. There were six cases of typhoid fever, one probably secondary. Suits filed against the city involved total claims of some $200,000.

SHIPPING. Vessels lying in port frequently make temporary connections with the municipal water supply mains on the docks. These vessels are also provided with sea pumps and use much water from "overside" for deck flushing and other purposes. The possibilities of cross connections are obvious, and instances of the pollution of the potable water supply by these means have been recorded.

NEW MAINS AND REPAIRS

The laying of water mains in trenches in the city streets, as commonly practiced, can hardly be regarded as a sanitary procedure. Contamination by the mud of the trench, perhaps saturated with cesspool drainage or leakage from sewers; the accumulation of miscellaneous debris within the pipe previous to its installation; and the operations of the workmen themselves during laying, lead inevitably to a contaminated main. Obviously all new work, whether extensions, replacement, or repairs, provides a ready means of reinfection of the water in the distribution system. Bacteriological examination of the water gives ample evidence that such reinfection does occur, often to a serious extent.

Occasionally epidemiological evidence of more conclusive character becomes available. In 1944 an epidemic of bacillary dysentery, involving some 3000 cases among industrial war workers and members of the Armed Forces, was traced to a contaminated water main.*

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* C. H. Kinnaman and F. C. Beelman, *Am. J. Pub. Health,* **34**, 948, 1944.

Corrective Measures. Disinfection of the water mains and pipes before they are turned into the system is a necessary and sufficient corrective measure. It is recommended that the lines be flushed to remove as much of the debris as possible, after which a solution of chlorine, in one of its available forms (see p. 473) is introduced. Depending upon the condition of the line, concentrations of 40 to 100 parts per million of available chlorine are employed and left in the system overnight or for a full 24 hours.

This treatment produces an immediate favorable result, but certain kinds of hemp packing, commonly employed in making up the leaded joints, appear to be normally contaminated with coliforms and to resist this treatment with chlorine. After a few days coliforms are likely to appear again in the water. Preliminary tests of the hemp or selection of a grade known to be free of this defect appear to be the only remedy.

Some of the war experiences in Great Britain have called attention to another possible source of contamination of water mains. Bombs, falling directly over a main, disrupted both the main and the adjacent sewer. The polluted water from the bomb crater later drained off into the water system and it became necessary to disinfect the latter before restoring it to use.

A peacetime counterpart of this situation is a matter of rather frequent occurrence in any city, namely, the bursting of an old main. Here also a large crater is developed into which all manner of pollution may enter. After repair, the line requires especially thorough disinfection before being put back in service. This point is the more important, because in the emergency it is desirable to return the main to service as promptly as possible; this is likely to be done at the expense of safety.

PLUMBING

Definition. Plumbing is the entire system of water supply and drainage, with all appurtenances, fixtures, traps, and vents, within or adjacent to a building. The domestic water is delivered through the plumbing system to the fixtures where it performs its assigned service and whence it returns through the plumbing to the sewer.

Public Health Significance. There are two distinct aspects to the public health significance of plumbing. Reference has been made to plumbing as one of the essentials of housing: a service of utility and convenience closely related to the health of the family. Again, plumbing, viewed as a part of the water contact cycle, has certain features the effects of which may reach beyond the individual establishment and adversely affect the health of the community.

PLUMBING AS AN ELEMENT OF HOUSING

Basic Requirements. Plumbing is planned and installed with reference to the adequacy and convenience of its several services, to reasonable freedom from wastage through leaky fixtures and from interruptions by stoppage, and to economy and permanency of construction.

Hot and cold water in kitchen and bathrooms—tubs, showers, hand bowls, and toilets in proper relation to the size of the household and properly disposed—and laundry facilities represent a reasonable standard of household equipment. In addition to these, but usually included in the plumbing contract, are the steam or hot water heating system and the gas supply. None of these matters requires detailed discussion except the purpose and function of traps and vents in the drainage system.

Traps. The older views as to the deadly nature of *sewer gas* have happily given way to one more in harmony with present-day knowledge. Nevertheless, every effort is made to prevent any open communication between the interior of the drainage system and the room.

It would clearly be undesirable to permit free access of vermin, rodents, or insects to the interior of the drainage system and back to the kitchen, but current practice is perhaps best defended upon the basis of odors. Within the drains there is, of necessity, much that is foul. All inner surfaces are coated with dense growths of slime-producing bacteria and fungi. These gather their food material from the passing stream and consume it in the familiar process which we know as decomposition or putrefaction. The process is, in fact, a perfectly normal utilization of food for the production of growth energy, but its waste products are evil-smelling gases, and may even include the definitely toxic hydrogen sulphide.

It is probably a natural corollary to our instinctive avoidance of putrefaction, that these gaseous products of decomposition tend to cause worry, loss of sleep or appetite, and, in more serious cases, headache and nausea. Some of the effects may be actual physiological reactions to such poisonous products as hydrogen sulphides, organic sulphides (mercaptans), and other volatile substances. Others may be purely mental reactions of distrust or avoidance, capable none the less of producing very real symptoms.

For the purpose of preventing free communication between the interior of the system and the air of the house a *trap* is placed immediately below each fixture (see Figure 61). This provides a water seal against the passage of air (and vermin) in either direction, but permits the free flow of water downward.

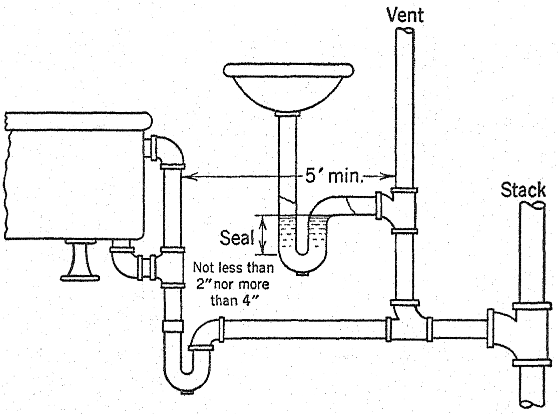

FIG. 61. Plumbing detail. Approved method of trapping and multiple venting.

VENTS. A sufficient and sudden discharge from a fixture on an upper story into the same stack might develop a positive pressure behind the trap sufficient to force its contents into the fixture, together with a volume of foul air. Similarly, passage of such a discharge past and below the level of the trap may result in a negative pressure sufficient to draw the contents of the trap into the drain.

To avoid both these possibilities, due in each case to air pressure differential, traps are provided with a *vent* (Figure 62). The vent connects a point just downstream from the trap to a point in the stack above the level of the highest side connection and thus tends to maintain essentially atmospheric pressure on both sides of the trap under all operating conditions. In general, each trap is separately vented, but in certain situations, like that illustrated in Figure 61, a group of closely spaced fixtures may be vented as one fixture.

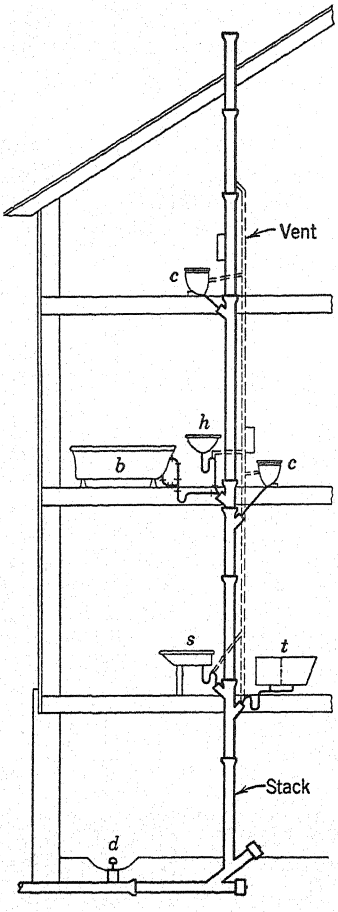

Fig. 62. Plumbing layout.

c	Water closets.
b	Bath tub.
h	Hand bowl.
s	Sink.
t	Laundry tubs.
d	Floor drain.

Corrosion. Many waters have definite corrosive tendencies for certain metals (see p. 292). Good water supply practice now takes note of this matter and regards noncorrosiveness, or nonaggressiveness, as a reasonable standard specification for a satisfactory domestic water. Corrective measures, however, are, at best, only partial. It is never possible to meet wholly and uniformly the normal fluctuations occurring continuously in raw waters. Furthermore, corrosion is a temperature function, so that it is not generally possible, even theoretically, to correct corrosiveness over the entire temperature range found within the household supply.

The water pipes, especially those of the hot water system, should be of materials reasonably resistant to any residual corrosive tendencies of the local water. In particular, the use of lead service pipes, between the street main and the house, a too-common practice, is be avoided wherever the water possesses any lead-dissolving tendency. Other types of water corrode iron and, eventually, galvanized (zinc-coated) iron. This is more likely to be so among waters that have been alum-treated as a preliminary to filtrations. Brass and copper are being increasingly recognized as the most suitable and, in the long run, the most economical materials for domestic water piping.

PLUMBING AS A PART OF THE WATER SYSTEM

Backflow and Back Siphonage. Possibilities of pollution of a potable water within the distribution system result when for any one of many reasons a negative pressure is temporarily established.

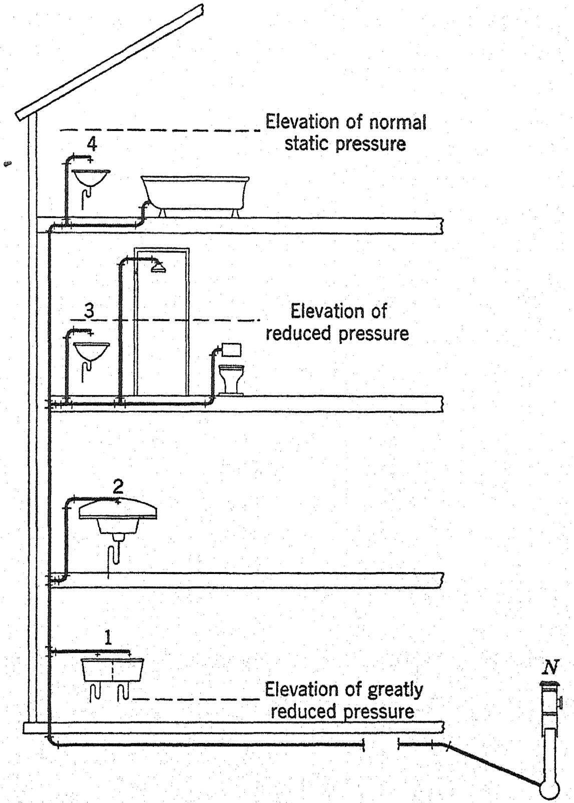

Fig. 63. Household water-piping system illustrating possibility of negative pressure and back-siphonage.

Water pipes are normally under pressure. In many situations, however, this pressure may be diminished or even become negative (less than atmospheric). Let us set up a diagrammatic water distribution system reduced to its simplest terms (Figure 63). At four elevations above the street level faucets permit withdrawal of water. The normal working pressure is none too good but it will deliver some water to the highest outlet.

Now suppose the three lower outlets to be opened, and the line to be of such small diameter or so corroded as to introduce a high friction loss to this combined flow. The pressure in the pipe drops to the lower level indicated. Water will flow from outlets 1 and 2 and will just dribble from outlet 3. At outlet 4, however, there is now a negative head or pressure; if this outlet be opened, air will enter and permit all the water above outlet 3 to flow down and out at this point.

Again, suppose the hydrant *N*, and possibly others in the neighborhood, is opened to flush out the main or for fire fighting. Now the pressure in the riser may fall to zero at its base, and the entire system will be put under a negative head. The same condition occurs every time the supply is cut off and the riser drained for repairs. Finally the water mains of the city may be outgrown or be of insufficient capacity, owing to a sudden population increase, so that, at times of maximum demand, the pressure sinks to a low level or even fails entirely in parts of the city. Thus there are many conditions resulting in a negative head or partial vacuum in the water pipes of a building usually thought of as being under pressure.

Thus the necessary condition for backflow or back siphonage is set up if there be any physical connection whereby water from any part of the plumbing system may return to the distribution system under the conditions of negative or lowered pressure. A simple example of such a condition is a partially filled bathtub provided with a single opening, serving as inlet and outlet, at the bottom. With a negative head or suction in the water line, back siphonage may occur even through the closed faucet, which is not designed to resist flow in the backward direction.

A more common example is the hand bowl with inlet extending below the full-water line. Not so obvious, but more dangerous, is the ordinary flushometer water closet (Figure 64). The internal connections are such that areas *a* and *b* are directly connected, and the contents of the bowl may be drawn back under reduced pressure in the mains.

PROTECTIVE ARRANGEMENTS. Two types of protective arrangements are available. The simplest and most obvious is the *air gap*. In the hand bowl, if there is a sufficient space between the lower rim of the inlet pipe and the upper rim of the bowl, no water connection exists, and backflow is impossible. In this situation, however, it is not quite sufficient merely to provide an air gap. A vigorous suction of air from the inlet pipe *too close to the water surface* will draw up water by a vortex action, similar to a waterspout. The specifications call for an air gap at least 1½ times the pipe diameter.

The air gap is suited to any situation in which the water enters the fixture at atmospheric pressure. But water pressure is essential for a satisfactory functioning of the flushometer valve, and for other equipments. This situation has been met by an ingenious use of the principle of the Venturi meter, Figure 64. At the *throat* or constricted section, the velocity is greatly increased. This decreases the pressure in accordance with Bernoulli's law; the sum of the pressure head (the height to which the water will rise in a pressure tube) and the square of the velocity remain constant during any change in cross section. This condition is well illustrated by the nozzle of a garden hose. At the outlet the pressure head is reduced to zero, having been totally converted into velocity head.

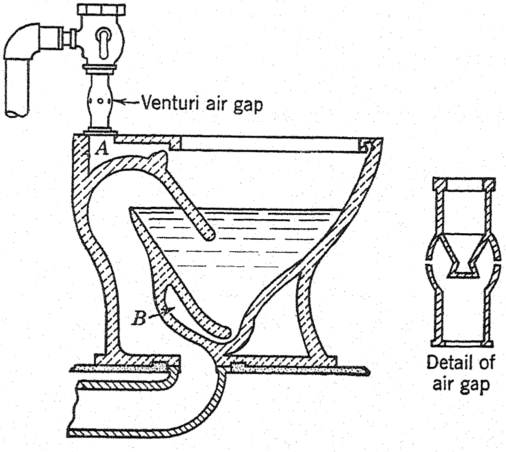

FIG. 64. Flushometer valve with Venturi air gap.

Such a high-velocity stream may be carried over an air gap and picked up at the other side in an expanding section where velocity is again reduced and pressure correspondingly regained. In this manner water under pressure may be carried across an air gap. Such a device is known in the code as a *backflow* or *back-siphonage preventer*.

Another type of blackflow preventer consists of an air vent placed in the line between any control valve, such as the flushometer valve, and the fixture. This vent has a large area of opening and is normally open when the fixture is not in use. Thus there is free communication between the pipe system and the air at this point, and negative pressure cannot develop. When the control valve is opened, water pressure within the vent presses a flap valve against the opening to prevent the outflow of water.

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CHAPTER 12

SEWAGE DISPOSAL AND THE POLLUTION AND SELF-PURIFICATION OF WATERCOURSES

Having dealt with the intake segment of the water contact cycle, water supply, we consider in the present chapter the two remaining segments of the cycle: the outgoing segment, the spent water supply or sewage; and the receiving segment, the natural watercourses. Again, it must be kept in mind, while developing the details of each of these segments, that water supply, sewage disposal, and the pollution and self-purification of streams are integral parts of one cycle and must, in the final analysis, be considered in their interrelationships and *in toto* as one problem.

SEWAGE DISPOSAL

The *disposal* of sewage, if the phrase is taken in its fullest sense, implies the ultimate and complete reversion of the organic matter to a form in which it is no longer subject to the biochemical reactions of decay and decomposition. This condition of ultimate stabilization does not mean complete oxidation to the mineral form. It is more nearly represented by the black humus of the forest loam.

To discharge sewage into a river or to bury it in the soil is only the first step in complete disposal. Sewage may be treated by mechanical or chemical means so that its physical characteristics are profoundly altered; it may be separated into its component parts, hidden in the ground waters or diluted in the depths of the sea; but in the great economy of nature it still remains to be disposed of. Only by combustion or by some equivalent and equally violent chemical process can the results of the natural process of complete disposal be simulated. In present-day practice and until some inexpensive method of chemical oxidation will have been found, *sewage disposal means the biochemical oxidation of organic matter through the agency of living organisms.*

This criterion of true disposal may seem somewhat extreme. In common parlance, to dispose of sewage is to remove it from sight, to get it out of the way. The expressions *disposal by dilution or disposal on land* are not infrequently used. Analysis of the meaning of such phrases, however, discloses a somewhat deeper significance than is at first apparent. Discharge into a stream already heavily polluted or upon land now so heavily overloaded that offensive conditions are bound to result would hardly be called disposal. There is always implied the thought that the means of disposal employed shall *take care* of the sewage in the sense of making it invisible and otherwise inoffensive. This calls for a considerable dilution in a reasonably pure stream or dispersion over an ample area of porous well-aerated soil.

In fact, the usual concept of disposal involves, unconsciously perhaps, those conditions which alone are capable of bringing about that complete biochemical stabilization which satisfies the criterion of true disposal. This criterion will therefore be employed in the further study of the subject, in order to avoid some confusion of thought, and to give a definite name to a definite though complex process which has suffered somewhat heretofore for lack of an accurate definition.

Disposal, under this broad definition, involves three major phases: collection of the liquid waste products from the homes, commercial establishments, and industries of the community, the sewer system; treatment of these wastes prior to discharge into a receiving body of water; and natural purification in the watercourses.

THE COMMUNITY SEWAGE COLLECTING AND DISPOSAL SYSTEM

TYPES. There are three types of sewerage systems:

Separate sanitary sewers—for collection of residential, commercial and industrial liquid wastes.

Storm water drains—for the collection of storm water from roof leaders, courtyards, sidewalks, streets, and land areas.

Combined sewers—a single collection system for both sewage and storm water in the same conduits.

The ideal plan, from the standpoint of the entire water contact cycle is the use of two completely independent systems, the sanitary sewers and the storm drains, with sanitary sewage excluded from storm drains and vice versa; for sanitary sewage must be treated while storm water need not be. Complete separation, however, requires not only proper design and construction but administrative regulations with adequate inspection and enforcement.

Combined sewers are obviously inconsistent with adequate treatment of sewage. Storm water discharge during heavy rainfall may be 100 to 200 times as great as the sewage flow from the same area. Treatment works designed to handle the entire combined flow during a storm period are obviously impracticable.

Consequently, where combined sewers are in use, intercepting sewers are connected to the combined sewer outlets by *regulator chambers* which divert the dry weather flow into the interceptor. During a storm, when the flow exceeds two or three times the dry weather flow, the regulators close, and the excess flow is diverted through the old outlet directly to the stream.

THE SANITARY SEWERAGE SYSTEM. The spent water from the plumbing system of individual buildings passes to the sanitary sewerage system. Unlike the water distribution grid, in which dead end lines are avoided, the sewers are laid out on a herringbone pattern in which each ultimate subdivision starts at a dead end—the *house connection*. From this point the system is conventionally divided into:

1. *Laterals,* the short small-diameter lines to which the house connections are made.
2. *Branch sewers,* serving groups of laterals.
3. *Main Sewers,* which receive the flow from several branches.
4. The *trunk sewer,* which collects the entire flow from one or more mains (Figure 65).

PUMPING STATIONS. Sewers are designed for free gravity flow when less than completely filled. The route taken by the main drainage lines depends upon topography. Although the slope (drop per foot) of the major drainage net is slight, the total fall from the upper end to the outlet of the system is substantial. Where a community is located on a side hill, it may be possible to work out one continuous free gravity-flow net serving the entire community. Where the topography is flat or the community is divided by ridges and valleys, two or more independent drainage systems may be required in order to keep the sewers at reasonable depths below the surface. In such instances, pumping stations are utilized to reduce cost of excavation for deep lines, by boosting the sewage flow from a deep to a more shallow sewer line, or by pumping from one drainage system over a ridge to combine the flow. Pumping stations must handle the varying flow as it comes and hence must operate continuously day in and day out.

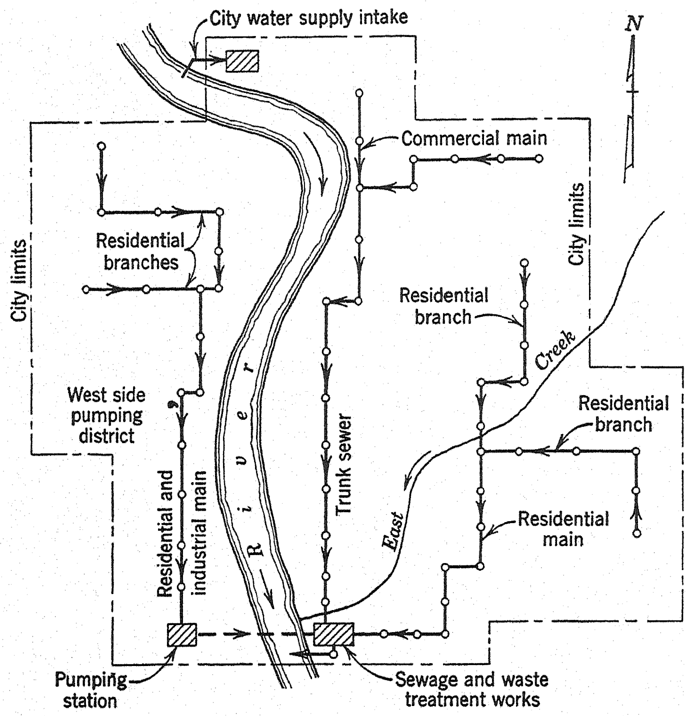

FIG. 65. Typical sewage-disposal system.

Separate sewerage system for sewage and industrial waste. Storm water drainage system not shown.

THE TREATMENT WORKS. The entire sewage flow is collected and delivered to the *treatment works* where a greater or less proportion of the total pollution load is removed before final discharge. Almost any desired degree of removal can be obtained by use of appropriate combinations of basic treatment principles, but in most situations some treatment is required if nuisance is to be avoided in the receiving stream. The extent of treatment necessary and sufficient is related to stream conditions and uses and can be discussed with better perspective in connection with the general discussion of the third segment of the cycle, the receiving stream.

Practical Considerations. Figure 65 and the foregoing discussion of a community system represent a somewhat idealized concept. Today most large cities have inherited a basic system designed and built many years ago, with subsequent additions and extensions. The art and science of sewage disposal at that period had not developed to the point where the public health significance of the complete water contact cycle was apparent or fully appreciated. Consequently, some of the sewage disposal systems built and in operation are not in conformity with our typical example. The more common faults which now appear in many of the older systems are:

Failure to provide for treatment prior to discharge to natural watercourses.

Failure to design the collecting system as an integral unit with a common outlet.

Failure to separate the collection of sewage from storm water drainage. (Early construction frequently combined sewage and storm water in the same collecting system.)

Failure to provide for industrial wastes as well as for municipal sewage.

Too frequently sewage disposal was limited to the construction of a series of sewer lines with direct discharges into the nearest stream without any provision for treatment. Failure to recognize the necessity for treatment readily explains the other faults. With no provision for treatment, it was not necessary to design the system to drain to a single outlet location, and, hence, sewers were constructed as needed, with outlets all along the waterfront throughout the city. Likewise, a separate system for the collection of sewage (*sanitary sewers*) independent of the storm water drains was not considered necessary, and house connections and laterals were connected to the large storm drains. Storm water flow so greatly exceeds the sewage flow that it is not feasible to accumulate drainage from large areas at a common outlet. Consequently, a storm water drainage plan, of necessity, involves a multitude of small drainage systems, with frequent outlets into near-by creeks and streams. Raw sewage is thus widely distributed throughout the community, polluting tributaries as well as the main watercourse.

In general, industries locate along watercourses for access to process water and discharge wastes directly to the stream. There was no object in collecting these industrial wastes for central treatment with the sewage in the absence of any provision for the treatment of the sewage itself. Consequently, the municipal sewerage system did not provide capacity for the inclusion of industrial wastes.

Now that the necessity for sewage and industrial waste treatment before discharge is recognized, modifications of the sewerage systems are required. It would not be practical to construct treatment works at every outlet, and, consequently, *intercepting sewers* are constructed, paralleling the watercourses, to collect the sewage and industrial wastes from the many outlets and convey them to a suitable site for treatment.

SEWAGE AND OTHER LIQUID WASTES

Quantity of Liquid Wastes. Sewage is the spent water supply of the community, and so it is natural that the quantity and variations in discharge of sewage will parallel water consumption. Where direct measurements of sewage flow are not available, water consumption records form a basis for estimating the volume of sewage. However, not all water delivered is discharged into the sewerage system. Some is lost in leakage from the water mains. This may vary from 10 to 50 gallons per capita per day, depending upon how well the water system is maintained. Some is used for street flushing and thus enters the storm water drains, rather than the sanitary sewers. In industrial areas, substantial quantities may be used as industrial cooling water, to be discharged, unpolluted, directly to a watercourse. Some water is used for lawn sprinkling and gardens. These represent deductions from water consumption.

On the other hand, direct surface drainage and infiltration of ground water represent additions to sewage flow over and above the spent water supply. Sanitary sewers are not intended to serve as storm water conduits or ground water drains. It is impossible, however, wholly to exclude water from these sources.

Roof leaders are frequently connected to the household plumbing system instead of discharging to the ground or storm water system. Ground water infiltration is a function of tightness of sewer joints and of ground water level. With good sewer construction infiltration should not exceed 600 gallons per day per inch of sewer diameter per mile of sewer. Old poorly constructed sewers may infilter as much as 100,000 gallons per day per mile of sewer.

Since sewage flow may differ measurably from water consumption it is customary to measure the quantity of sewage produced in typical residential, commercial, and industrial areas. These flows are then converted into per capita rates which, with the aid of population predictions, can be used to obtain estimates of future quantities for each of the zoned areas of the city.

SOURCES AND CHARACTERISTICS OF LIQUID WASTES. Whereas quantity of waste is the important consideration in the design of the sewerage system, knowledge of its characteristics and properties is essential in the design of treatment works and in the analysis of ultimate disposal in the natural watercourse. This calls for information as to the strength of the waste as a measure of the quantity of pollutional matter carried in the spent water supply.

The residential and commercial sewage of a community, the municipal sewage, carries rather definite per capita contributions of pollution. Industrial wastes, on the other hand, vary widely. It has been seen that the two best measures of strength of liquid wastes (from the point of view of disposal) are the suspended solids and the biochemical oxygen demand (BOD).

For fresh municipal sewage the quantities of these two constituents are quite uniform; 0.2 pound and 0.24* pound per capita per day, respectively. Their concentrations, however, vary widely, depending as they do upon the per capita volumes of spent water in which they are carried. Certain industries produce rather uniform quantities of waste organic matter measured in these same terms, and they can therefore be evaluated in terms of equivalent population by the following relations:

POPULATION EQUIVALENTS

Suspended solids (s.s.) $$\frac{\text{Lb per day of s.s.}}{0.2}$$

BOD $$\frac{\text{Lb per day BOD (ultimate)}}{0.24}$$

or

$$\frac{\text{Lb per day BOD (5-day)}}{0.165}$$

Table 42 (from studies by the U. S. Public Health Service) indicates the population equivalents of certain industrial wastes per

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* This value refers to the ultimate BOD, the preferable unit. The 5-day value, commonly but improperly referred to as BOD, is 68 per cent of the ultimate or 0.165 pound per day.

TABLE 42

Summary of Waste Discharges, Sewered Population Equivalents and Employees per Unit of Production, with Typical Analytical Results, for Various Industrial Wastes

Industry	Unit of Daily Production	Employees per Unit	Wastes, Gal per Unit	Typical Analyses ppm		Sewered Pop. Equivalents†		Remarks
				BOD 5-day	Susp. Sol.	BOD	Susp. Sol.	
Brewing								
	1 bbl, beer	0.25	470	1200‡	650	19	9	Spent grain dewatered.
	1 bbl, beer	0.25	470	800‡	450	12	6	S.G. sold wet.
Canning								
Apricots	100 cases, #2 cans	....	8000	1020	....	410	....	
Asparagus	100 cases, #2 cans	....	7000	100	30	35	9	
Beans								
green	100 cases, #2 cans	....	3500	200	60	35	9	
lima	100 cases, #2 cans	....	25,000	190	420	240	440	
pork and	100 cases, #2 cans	....	3500	920	225	160	33	
Beets	100 cases, #2 cans	....	3700	2600	1530	480	240	
Corn, cream style	100 cases, #2 cans	45	2500	620	300	75	30	
wh. kernel	100 cases, #2 cans	....	2500	2000	1250	250	130	
Grapefruit								
juice	100 cases, #2 cans	....	500	310*	170*	8*	3*	* Excl. peel bin wastes.
sections	100 cases, #2 cans	....	5600	1850	270	520	63	
Peaches–pears	100 cases, cans	....	6500	1340	....	440	....	Size of can unknown.
Peas	100 cases, #2 cans	1	2500	1700	400	210	40	
Pumpkin (squash)	100 cases, #2½ cans	....	2500	6400	1850	800	190	
Sauerkraut	100 cases, #2 cans	....	300	6300	630	100	8	
Spinach	100 cases, #2 cans	....	16,000	620	....	490	....	
Succotash	100 cases, #2 cans	....	12,500	520	250	330	130	

Tomatoes								
products	100 cases, #2 cans	....	7000	1000	500	350	150	
whole	100 cases, #2 cans	6.5	750	4000	2000	150	60	
Coal Washery	1000 tons coal washed	6	....	15	115,000	....	....	
Coke	100 tons coal carbonized	8	360,000	85	....	1500	....	Wastes cause tastes and odors.
Distilling, Grain								
Combined wastes	1000 bu grain mashed	40	600,000	230	360	3500	2300	Excl. intentionally disch. slop.
Thin slop	1000 bu grain mashed	40	....	34,000	....	55,000	....	
Tailings	1000 bu grain mashed	....	....	740	....	50	....	
Evaporator condensate	1000 bu grain mashed	....	....	1200	....	1500	....	
Molasses	1000 gal 100 proof	8	8400	33,000	3270	12,000	1000	Molasses slop.
Cooling water	1000 gal 100 proof	....	120,000	....	....	....	....	
Meat								
Packing house	100 hog units of kill	30	550	....	....	77*	25*	* Paunch manure to sewer.
	100 hog units of kill	30	550	900	650	24	14	(1 cattle equals $2\frac{1}{2}$ hog units = $2\frac{1}{2}$ calves = $2\frac{1}{2}$ sheep.)
Slaughter house	100 hog units of kill	20	160	2200	930	18	6	
Stockyards	1 acre	....	25,000	65	175	80	180	
Poultry	1000 lb live wt.	6	2200	....	....	300	160	Av. wt. = 4.5 lb per animal.
Milk								
Receiving station	1000 lb raw milk and cream	0.15	180	500	....	4	2	
Bottling works	1000 lb raw milk and cream	0.89	250	....	....	6	3	
Cheese factory	1000 lb raw milk and cream	0.38	200	100	750	16	9	

From *U. S. Pub. Health Service Ind. Waste Guides*, Ohio River Pollution Control, *House Doc. 266, 78 Congr.*, 1st Session.

† Persons per unit of daily production.

‡ Ultimate BOD.

TABLE 42 (*Contd.*)

Industry	Unit of Daily Production	Em-ployees per Unit	Wastes, Gal per Unit	Typical Analyses ppm		Sewered Pop. Equivalents †		Remarks
				BOD 5-day	Susp. Sol.	BOD	Susp. Sol.	
Milk								
Creamery	1000 lb raw milk and cream	0.16	110	1250	660	6	3	
Condensery	1000 lb raw milk and cream	0.47	150*	1300	750	7	4	* Excl. vacuum pan water.
Dry milk	1000 lb raw milk and cream	0.39	150	480	....	6	3	
General dairy	1000 lb raw milk and cream	1.09	340	570	540	10	5	
Oil Field	100 bbl crude oil	1.3	18,000	....	....	....	....	
Oil Refining	100 bbl crude oil	3	77,000	20	50	60	120	1 bbl = 42 gal.
Paper								
Paper mill	1 ton of paper	4.4	39,000	19	452	26	520	No bleaching.
Paper mill	1 ton of paper	4.6	47,000	24	156	40	220	With bleaching.
Pasteboard	1 ton of paper	2.1	14,000	121	660	97	445	
Strawboard	1 ton of paper	1.4	26,000	965	1790	1230	1920	
Deinking	1 ton of paper	....	83,000	300	....	1250	....	Old paperstock.
Paper Pulp								
Groundwood	1 ton dry pulp	2.5	5000	645	....	16	....	
Soda	1 ton dry pulp	3.0	85,000	110	1720	460	6100	
Sulphate (Kraft)	1 ton dry pulp	....	64,000	123	....	390	....	
Sulphite	1 ton dry pulp	3.1	60,000	443	....	1330	....	
Tanning, Vegetable	100 lb raw hides	7	800	1200	2400	48	80	

Tanning, Chrome	100 lb raw hides	....	....	....	....	24	40	
Textile								
Cotton								
Sizing	1000 lb goods processed	....	60	820	....	2	....	
Desizing	1000 lb goods processed	....	1100	1750	....	96	....	
Kiering	1000 lb goods processed	....	1700	1240	....	108	....	
Bleaching	1000 lb goods processed	....	1200	300	....	17	....	
Souring	1000 lb goods processed	....	3400	72	....	12	....	
Mercerizing	1000 lb goods processed	....	30,000	55	....	83	....	
Dyeing								
Basic	1000 lb goods processed	....	18,000	100	....	100	....	
Direct	1000 lb goods processed	....	6400	220	....	71	....	
Vat	1000 lb goods processed	....	19,000	140	....	130	....	
Sulphur	1000 lb goods processed	....	5400	1300	....	360	....	
Developed	1000 lb goods processed	....	14,400	170	....	120	....	
Naphthol	1000 lb goods processed	....	4800	250	....	59	....	
Aniline black	1000 lb goods processed	....	15,600	55	....	41	....	
Print works	1000 lb goods processed	....	4500	95	....	15	....	
Finishing	1000 lb goods processed	....	6	1250	....	0.4	....	
Rayon manufacture	1 cord wood distilled	35	680,000	30	....	1000	....	Wood distillation process.
	1000 lb rayon produced	64	160	4.4	19	35	130	Cupra-ammonia process.
	1000 lb rayon produced	50	140	110	96	800	580	Viscose process.
Rayon hosiery	1000 lb hose produced	....	9000	330	....	150	....	Boil off and dye wastes.
Silk hosiery	1000 lb hose produced	....	13,700	1720	....	1180	....	Boil off, dye and finish wastes.
Woolen mill	1000 lb finished goods	....	70,000	114	....	400	....	Scouring and dyeing—no grease wool.
	1000 lb finished goods	....	240,000	125	....	1500	....	Scouring and dyeing — 100% grease wool.

From *U. S. Pub. Health Service Ind. Waste Guides*, Ohio River Pollution Control, *House Doc. 266, 78 Congr.*, 1st Session.

† Persons per unit of daily production.

unit of daily product output. It is best, if feasible, to make an industrial waste survey in important studies for local planning.

FACTORS AFFECTING SEWERAGE PLANNING. In addition to technical factors (lines, grades, and sizes of sewers), matters of policy affect the planning of a sewerage system. Sewers are built to serve a future need 25 to 30 years hence, and, consequently, questions of community growth and shifts in population within the community are involved. This necessitates a study of the social and economic as well as the population trends of the entire region or drainage area of which the particular city is but a part. Within the city, zoning policies are important, as they tend to direct the internal development of residential, commercial, and industrial areas. Coordination of extensions with water supply is essential.

In metropolitan areas, where there are many separate civil divisions, coordination among political units for joint action in the construction of a basic drainage plan and joint treatment works serving a group of towns within a natural drainage district greatly affect the internal plan within each town. Joint action for logical *service areas* crossing political boundaries is to be encouraged wherever public health interests and economics indicate a sounder solution than the construction of a non-integrated patchwork of individual systems on strictly political boundary lines.

Financing of works and the capacity to pay are frequently more important than technical matters when needed facilities are to be provided. Sewage disposal is in competition with many other community facilities (schools, parks, streets) which have a more direct appeal. The programming of all needed public works on a long-time basis, with an annual review of relative priority, affords the public health engineer an opportunity to promote the sewage disposal needs on a more rational basis in relation to other needs.

With questions of policy crystallized, many technical factors affect the specific *sewer plan*. Existing facilities are surveyed to determine the location of other utilities, water mains, storm drains, gas lines; the type of roads and pavements; and the actual location of existing buildings to be served. Topography is important, including location of all streams and lakes, high and low water elevations, contours of the natural ground, official grades of streets, the outlines of natural drainage districts, the character of the soil, rock, sand, dry, or wet. The location and number of sewage treatment plants are obviously controlling factors. The cost of interceptor sewers or mains and trunks and booster pumping stations must be balanced against the disadvantages and cost of construction and operation of more than one treatment works.

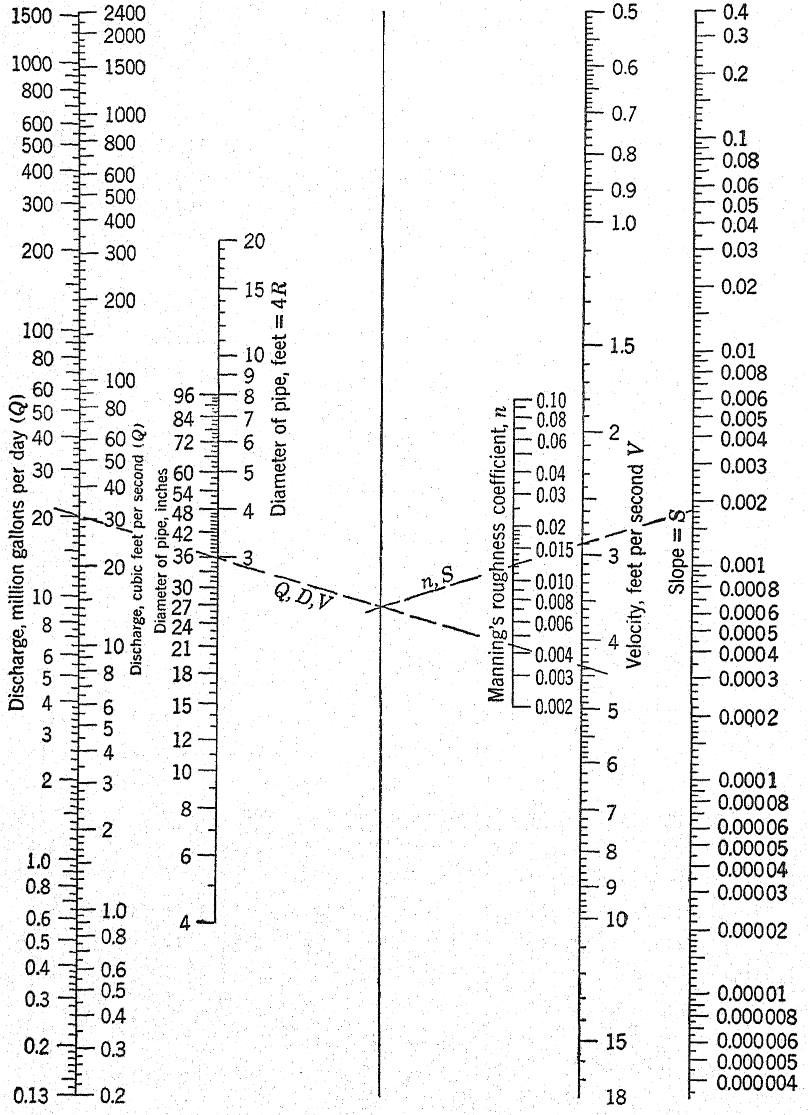
REQUIREMENTS AND REGULATIONS GOVERNING DESIGN AND CONSTRUCTION. Sewers and pumping stations are designed for a period of 25 to 30 years hence. Laterals and branch sewers are designed for a capacity, flowing full, four times the average daily flow, with minimum capacity not less than 20 gallons per day per foot of sewer. Regardless of capacity requirements, no sewer should be less than 8 inches in diameter. Interceptor, main, trunk or outfall sewers should be designed to carry the maximum hourly flow on the maximum day, or, in the absence of specific information on variations in discharge, 250 gallons per capita per day, with due allowance for industrial wastes, sewers flowing full.

The *velocity* in sewer pipes must be sufficient to prevent the deposit of suspended matter in the pipe lines under any conditions of flow. Since pipes are designed for full capacity two to four times the average daily flow 25 years hence, they are practically always flowing substantially less than full. The velocity of partially filled pipes should not fall below 1.5 feet per second at low flows, and, generally, a velocity of 2.5 to 3 feet per second when flowing full will insure satisfactory velocity at low flows. At the other extreme, the velocity should not exceed 8 to 10 feet per second, in order to avoid abrasion of the pipe invert. Figure 66 is a convenient nomographic chart showing the relation among discharge Q, pipe diameter D, velocity V, slope S, and coefficient of roughness n. Figure 67 may be employed to determine the hydraulic elements of the sewer flowing less than full.

Access manholes are provided to permit cleaning. They are spaced at intervals not exceeding 500 feet for pipe sizes less than 18 inches and are also provided at all ends, intersections of lines, and changes in alignment or grade.

Sewers are usually constructed of *vitrified clay pipes* or *precast reinforced concrete*. Large diameters, 6 feet and over, may be built in place, of brick or reinforced concrete.

The design of *pumping stations* is an involved engineering problem, but some of the major sanitary requirements may be briefly indicated. The primary requisite is continuity of service. Even temporary failure may result in backing up the sewage into cellars or overflow from manholes.



Courtesy of Thomas R. Camp

FIG. 66. Alignment chart for flow in sewers.

Manning's formula: $V = \dfrac{1.486}{n} R^{2/3} S^{1/2}$

The sewage should enter a *receiving chamber* (*wet well*) separate from a chamber in which the pumps are located (*dry well*). Thus, the pumps are readily accessible for repair. The practice of submerging the pumps in the sewage in a common wet well is undesirable from an operating standpoint. The wet well is designed with sloping bottom to prevent accumulations of suspended matter, which cause odor. Solids and liquids should continuously pass to the pump suction lines. *Screens* and *shredders,* or *comminutors* (see p. 550), should be installed at the inlet to the wet well to intercept large particles which would clog the pumps.

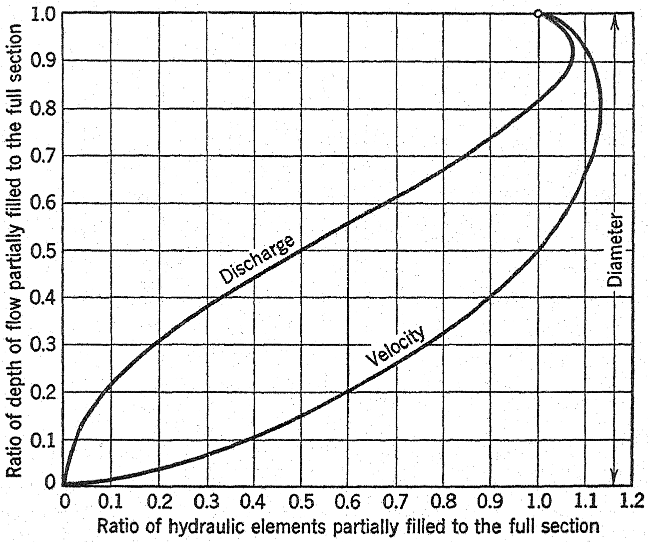


FIG. 67. Hydraulic elements for circular section.
Approximate for ordinary sewerage problems.

Centrifugal pumps are commonly used; at least three should be installed. The capacities are balanced against the pumping load approximately as follows: one pump of capacity about halfway between the average daily flow and the minimum daily flow; another of capacity so that, with the first pump in operation, their combined capacity will handle maximum hourly discharge on the maximum day; and the third pump, a factor of safety, which can handle alone the maximum hourly discharge on the maximum day.

A *dual source of power* is generally provided to protect against power failure. Where electric grids permit, two independent power sources are connected to the station so that, if a storm severs service from one source, a second source is immediately available. Where such electric service is not available, it is essential to install a gas engine stand-by power unit, either connected to an electric generator or directly connected to the largest pump.

Motors are placed at first floor level, which should be one foot above the maximum high water elevation to prevent stoppage from flooding.

Automatic controls, operated by floats actuated by the level of the sewage in the wet well, cut the pumps in or out as needed, to handle the variation in the quantity of incoming sewage. The controls can further be connected to an alarm system to warn operating personnel in the event of a pump failure.

Ventilation of both wet well and dry well is essential. Sewage contains gasoline and other combustibles which are harmful to operating personnel and constitute an explosive hazard. Septic sewage may give rise to hydrogen sulphide, highly corrosive to metal work and machinery and toxic to human beings.

NATURAL WATERCOURSES

The intake and outgo segments of the water contact cycle concern water diverted from its natural course into a circuit through the community for primary and secondary uses. We now consider the receiving segment of the cycle, water confined in natural watercourses, and its tertiary uses. We speak of water in natural courses as the receiving segment, since that which leaves as stream flow or by evaporation and transpiration returns through rainfall, as surface runoff and ground water seepage; that which is diverted as water supply returns as untreated sewage or industrial waste or as effluent from treatment works. Thus, the stream constantly receives water used again and again by nature in its hydrologic cycle, as well as water used by man in his contact cycle.

We shall deal here with the characteristics and uses of the natural watercourse, but it should be kept in mind that the stream is merely an integral part of the whole contact cycle. Nor should this arbitrary designation of the stream as the receiving segment divert attention from the fact that the cycle neither begins nor ends. The receiving segment, in turn, becomes the source of water for primary and secondary uses of communities below and is itself the water supply for various tertiary uses some of which are dealt with in this section. The public health engineer is charged, not only with the protection of streams as sources of domestic water supply, but equally with the development of sound policies leading to balanced multiple uses, with maximum utility consistent with conservation of our great water heritage.

Quantity and quality are the primary considerations in any problem of water use. We have previously considered quantity of water, its occurence, distribution, and variation, under Hydrology (chapter 9). In this present chapter we turn to quality characteristics and changes in natural watercourses.

STREAM POLLUTION AND SELF-PURIFICATION

Every stream or other body of water has a certain limited capacity to dispose of sewage and other organic wastes. The utilization of this capacity, like that of any other asset, must be paid for. In this instance, payment consists of a loss, partial or total, of reserve capacity and the production of certain nuisances. The stream capacity itself, and hence the depreciation of its reserve, can best be defined and measured in terms of resultant nuisances, so that these provide the most satisfactory basis for the discussion of what has been called sewage disposal by dilution.

TYPES OF NUISANCE

For convenience we may discuss the nuisances that result from stream pollution under three major types: *physical, chemical,* and *bacterial.* This classification is the more useful because each of these types of pollution represents a corresponding type of remedial treatment to which reference is later made.

Physical Nuisance. The mere deposit of suspended solids upon the bed and banks of a stream or in a millpond results in a physical condition having certain nuisance characteristics. Regardless of its effect upon the water, such deposits may destroy certain useful values of the stream such as millpond capacity or give rise to offensive odors of putrefaction of organic matter. Other typical physical nuisances are unsightliness, due to floating materials, scum, oils, and debris, and dissolved and suspended matters causing turbidity and color.

The stream's capacity to neutralize these physical effects is determined by the two characteristics of its flow: volume and velocity. In a swiftly flowing stream, deposit in bulk does not occur, and solids are comminuted and retained in the flowing stream. Dilution of the offending wastes likewise reduces discoloration, and odor. These physical nuisances are of relatively minor influence when compared with nuisances of other kinds. Treatment for their prevention is relatively simple and usually constitutes the first stage in a major waste treatment project.

CHEMICAL NUISANCE. The biochemical oxidation of organic matter in a stream results in changes of a chemical nature, the most conspicuous of which is a loss of the oxygen normally dissolved in the water. In extreme cases this may lead to total exhaustion of the oxygen, production of odors of putrefaction, and the destruction of green plant and fish life. Stream capacity to deal with this type of nuisance is based wholly upon oxygen relations and is formulated in terms of the *oxygen balance*.

Other types of chemical nuisance may arise from the discharge of industrial wastes. These include substances toxic or otherwise injurious to fish; acids which injure concrete structures and boiler tubes and make the water less suitable for domestic use and more difficult to treat; and organic compounds like phenol which yield odor to the water, especially after chlorination. Dilution, or streamflow, measures the stream's capacity to deal with these kinds of pollution.

BACTERIAL NUISANCE. The third type of nuisance deals wholly with the possible presence in the sewage, and thus in the polluted stream, of pathogenic bacteria capable of causing disease. This may be referred to then as the *bacterial nuisance*. It is of general significance, but particularly with reference to the subsequent use of the water as a source of domestic supply (primary use) or to its passage over shellfish areas or bathing beaches (tertiary uses).

Stream capacity, for this particular type of nuisance, involves dilution also, but is principally a matter of time of passage from the point of pollution to the area of use.

SELF-PURIFICATION. In each of the three types of nuisance mere dilution in the stream volume has been indicated as an element in stream capacity. Bacterial and chemical (organic) pollutions, however, are subject to other influences, the true *disposal* influences, which constitute the basis of what is known as the *self-purification* of water. The paramount importance of self-purification in stream utilization justifies a somewhat detailed discussion of its nature and underlying principles.

BACTERIAL SELF-PURIFICATION

One of the most interesting phenomena which will come to the attention of the student of water supply is the *natural self-purification* of water from a bacteriological standpoint. It has long been observed that a stream, once polluted with bacteria of sewage origin and then flowing for a considerable distance without further increments of pollution, tends to improve its condition.

POTOMAC RIVER STUDIES. This effect is well illustrated in the data obtained during a study of the Potomac River below the District of Columbia.* The sewage of the District was discharged into the river after receiving certain minor treatments designed to remove the gross suspended matter. An intensive study of the river was made over a period of 10 months. Cross sections of the river were selected at various distances below the city at each of which the water was examined for bacteria daily or at least three times a week. Samples were collected at stations across each section and at various depths to secure better cross-sectional average values.

Table 43 has been computed from the data. It represents three of the cross sections located at 2, 14, and 42 miles below the city, respectively. The estimated time of passage from the city to the lower station and the mean temperatures for the month are given.

The data show the decrease in the numbers of bacteria of sewage origin that takes place in a flowing stream and due wholly to natural causes. They are too meager, however, to provide a basis for further mathematical study of the relations involved, and of the form and constants of the normal bacterial death-rate curve, the more exact determination of which is a matter of considerable interest in our present consideration of self-purification.

THE GEOMETRIC DEATH RATE. In various laboratory studies of the death rates of bacteria under the influence of heat, germicidal chemicals, or merely the absence of food, it has been found that the numbers of surviving bacteria tend to form a geometrical progression

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* H. S. Cumming, *U. S. Pub. Health Service, Hgy. Lab. Bull.* **104**, 1916.

TABLE 43

Bacterial Self-Purification of the Potomac River Below Washington, D. C.

Compiled from data by Cumming

Station	Geisboro Point	Marshall Hall	Maryland Point	Approximate Time of Flow, Washington to Maryland Point, Days	Mean Temp. °F
Miles below Washington, Nautical	2	14	42		
Month 1913	*B. coli per 100 cc.*				
Aug.	61,700	4,800	4	100	81
Sept.	30,600	2,400	7	37	73
Oct.	38,900	8,500	11	25	68
Nov.	23,100	13,700	75	26	52
Dec.	19,900	6,400	32	28	46
1914					
Jan.	18,400		690	14	37
Feb.	2,400		470	14	37
Mar.	9,800	9,100	350	15	39
Apr.	8,600	7,800	20	23	50
May	19,900		25	28	64

in time. That is, during any interval unit of time, they are reduced by a constant proportion of the number existing at the beginning of that interval. This is merely the opposite of the geometric rate of population increase during which two become four, four become eight and so on, during equal intervals of time. On a logarithmic scale, values separated by equal intervals have the same ratio to one another, regardless of their position in the scale, so that, if logarithms of surviving numbers are plotted against time, a set of data conforming exactly to the law of geometric decrease will plot as a straight line.

Cumming's data, including those from several stations not included in Table 43, have been plotted in this manner in Figure 68. The straight line indicated is as good a representation of the facts as these data justify. It is plain that there are other factors (such as water temperature) in the determination of the bacterial death rate which are not included in the simple geometric law. On the other hand, it appears that the data, taken as a whole, tend to reproduce that law.

Ohio River Studies. A much more comprehensive study along similar lines was made by the U. S. Public Health Service on the Ohio River.* Continuous observations were made at many stations on the river and over parts of three years. Analysis of these data shows first that there is a short stretch below the city discharging sewage into the stream, in which there is an apparent increase in bacterial numbers.

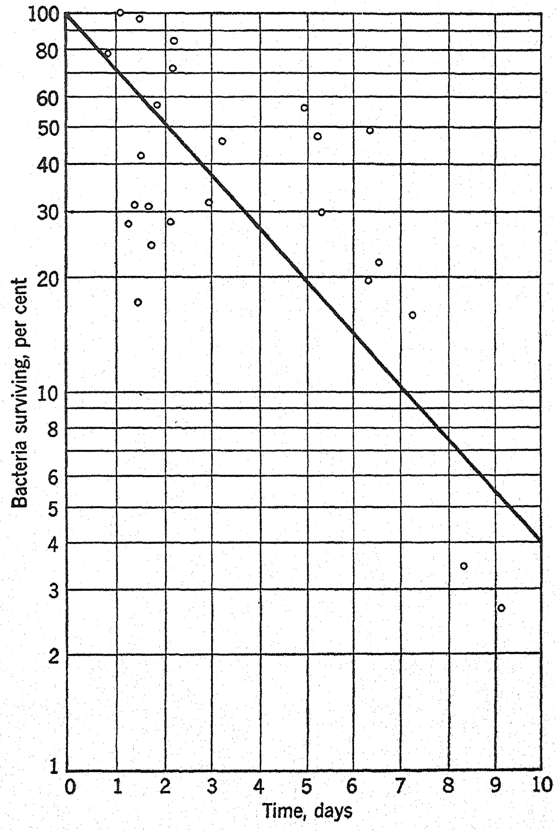

Fig. 68. Bacterial death rates, Potomac River. (Cumming's data.)

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* W. H. Frost and H. W. Streeter, *U. S. Pub. Health Service, Pub. Health Bull.* **143**, 1924.

Below the point of maximum numbers there is a steady and regular decrease in numbers which follows the logarithmic law with some degree of approximation. Closer analysis, especially of the lower values after about 90 per cent of the total numbers have disappeared, suggests that the death rate is compounded of at least two such geometric rates; two or more independent rates such as would result from the simultaneous disappearance of two or more groups of bacteria with different degrees of resistance. Two such terms yield a curve of decrease which fits the data satisfactorily, but it is probable that a curve compounded of several such terms would probably be more representative if the data were of sufficient accuracy to justify further refinement.

The survival curve obtained for the *Escherichia coli* has been plotted in Figure 69 for cool weather and warm weather conditions. The death rate, as measured on the Ohio, is evidently greater than that found on the Potomac—a further illustration of the complexity of the problem when accurately studied.

As a practical conclusion, it appears that throughout the year a reduction amounting to 85 or 90 per cent occurs during the first two days, the lower value during the cooler months. Beyond this time, 2 days, the temperature effects become more noticeable, so that a 99 per cent reduction requires about 17 days of passage in the winter months and only about 5 days in summer.

Lakes and Reservoirs. Large bodies of water, such as lakes and reservoirs, differ from streams in that long times of storage are often provided. This accounts in part for their generally greater purity as compared with running streams. Indeed, in view of what has been said, it must be evident that, as concerns freedom from bacteria of sewage origin, it is not *running water* which purifies itself, according to the familiar adage, but *standing* water, in which the element of time permits the operation of natural self-purification.

A striking example of this has been observed in Lake Erie. The waters of the Detroit River were found, during an investigation by the International Joint Commission in 1913, to contain several hundred coliforms per milliliter. Yet samples taken from the central sections of Lake Erie showed no traces of this test organism in 100 milliliter samples, despite the fact that these waters had for the most part come through the Detroit River.

Similar remarkable evidences of self-purification were noted by Houston in connection with the storage reservoirs of the London water supply system. In the water of the Thames above the intake works, *Escherichia coli* were present in such numbers as to yield positive tests in about 50 per cent of the 1/10-milliliter samples tested. Passage through a reservoir having a displacement volume of approximately 15 times the daily flow reduced these numbers by 96 per cent; and in another reservoir, with a 14-day displacement, by 94 per cent.

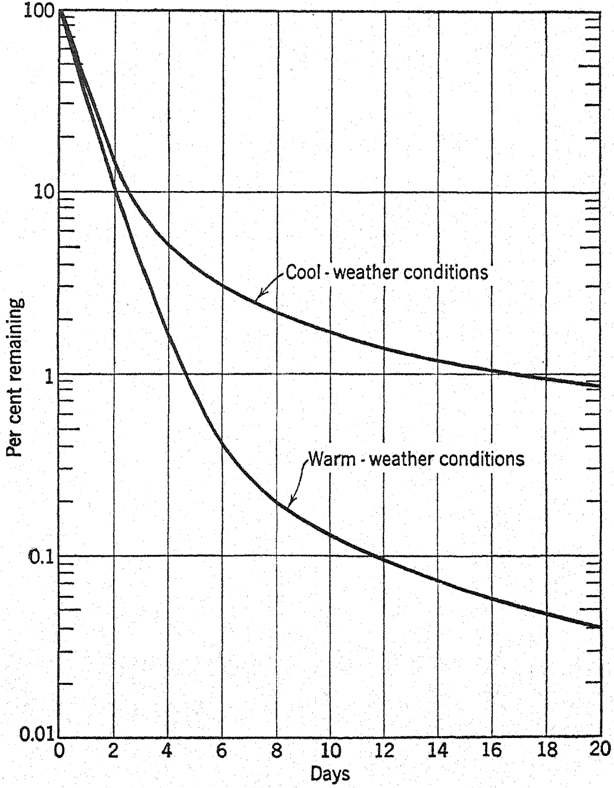

FIG. 69. Death rate curves of *E. coli* in the Ohio River.

THE CAUSES OF NATURAL SELF-PURIFICATION. Natural self-purification has been variously attributed to some inherent power of rapidly flowing water (obviously not an influence in lakes), to sedimentation (not operative in swiftly flowing streams), and to sunlight, competitive life, and other causes. Many of these influences are undoubtedly at work, but it appears that the predominant influence and chief cause of the phenomenon is the natural tendency of bacteria of intestinal origin to die in the unusual and generally unfavorable environment of natural watercourses, particularly as regards lack of food and low temperature.

The organisms *Escherichia coli* and *Eberthella typhosa* can both be grown in the laboratory. Given ample food and an optimum temperature (that of the human body, 37°C) they multiply at a rapid rate. The rate of multiplication becomes less at lower temperature. Under exactly similar conditions, but in water instead of in a rich food medium, the same organisms tend to die, and the death rate likewise *decreases* with lowered temperature. The same temperature change which speeds up the rate of living, speeds up the rate of dying. The situation seems to be quite like that of a candle; the faster it lives, the sooner it is consumed. Under stream conditions bacteria appear to die from lack of food and from reduced food-getting activity.

BIOCHEMICAL SELF-PURIFICATION. THE OXYGEN BALANCE

A type of self-purification distinctly different from that just considered is involved in that natural process whereby organic matter, in general, is gradually decomposed, oxidized, and rendered innocuous by living organisms in the stream, the normal stream bacteria, and other low forms of plant and animal life. The effects upon the receiving stream of organic pollution and of the biochemical reactions involved in its disposal may be most profitably studied in terms of the *oxygen balance*. The complete treatment of this relation is complicated but its basic principles may be summed up here.*

Oxygen Resources. Atmospheric or elementary oxygen is soluble to a limited extent in water. In this state it is called *dissolved oxygen* or, for brevity, the D.O. All natural waters exposed to the atmosphere dissolve oxygen and tend to maintain a condition of *saturation*, which is the value of the oxygen concentration in equilibrium with the atmosphere (see Table 34).

The practical and accepted definition of saturation, just given, has one theoretical shortcoming which, unless clarified, may lead

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* For a more detailed treatment see the author's *Stream Sanitation.*

to misunderstanding. Green plants growing in water release oxygen in nearly pure form. It has been pointed out earlier (p. 290), in discussion of the laws of solubility of gases in water, that under such conditions the solubility of oxygen would be about five times as great as that under normal atmospheres. Hence, it frequently happens that waters supporting heavy growths of plant life are "supersaturated" with oxygen in the sense of our standard table of saturation values.

REAERATION. If, for any reason, the concentration of the dissolved oxygen in water exposed to the air falls below the saturation value, an unstable condition exists, and the water renews its oxygen supply from the atmosphere. This is *reaeration.*

Reaeration is a complex phenomenon. It involves solution by actual contact at the surface, diffusion of the dissolved oxygen from points of higher to those of lower concentration, and mixing by agitation or turbulence. Both diffusion and turbulence are functions of depth, and turbulence is related to velocity of flow and character of the channel. Wind, waves, and tidal currents, as well as passing vessels, all contribute to mixing by turbulence and thus to reaeration.

One important principle, however, remains fixed among these involved terms. *Under any given set of river conditions, the rate of reaeration is directly proportional to the saturation deficit.* A saturated water will dissolve no more oxygen. Its deficit is zero. A water at 50 per cent of saturation (deficit also 50 per cent) will dissolve oxygen at five times the rate of one at 90 per cent (deficit 10 per cent), and at one-half the rate of one containing no oxygen (deficit 100 per cent).

Useful rules of at least relative and qualitative value are: Reaeration proceeds more rapidly in shallow than in deep water, in running streams than in quiescent ponds, in the more turbulent than in the smoother stream, and in the upper levels of deeper streams and lakes. In clear, shallow waters, exposed to sunlight, green plants, growing on the bottom or as *plankton* or free floating forms, may contribute a useful quantity of oxygen.

The actual rate of reaeration, under stream conditions, has been determined experimentally in a few instances. The basic formula,

$$-\frac{dD}{dt} = K_2 D$$

or the rate of loss in the deficit D (rate of reaeration) is proportional to the deficit, integrates to

$$D_t = D_a \times 10^{-k_2 t}$$

which expresses the relation between the deficit, D_t after any time t, the initial deficit D_a, and the coefficient of reaeration, k_2 (that is, $k_2 = 0.434K_2$, to transform to common logs).

The reaeration coefficient k_2 reflects the influences of stream depth, velocity, and turbulence of mixing. For large rivers of moderate depth and velocity (time t being taken in days), k_2 is approximately 0.25; for swift shallow highly turbulent streams, as high as 0.5; and for deep pools, lakes, and reservoirs or deep sluggish streams, as low as 0.05. The selection of k_2 requires experienced judgment and, generally, is checked against stream survey data of the specific watercourse involved.

APPLICATION OF REAERATION FORMULA. With these values given, it is possible to compute the reaeration in a stream under any assigned set of conditions. Assume the existing deficit to be 50 per cent of saturation, the temperature 12 degrees centigrade, and the reaeration coefficient 0.25. Then

$$D_t = D_a \times 10^{-0.25t} = 0.56^t D_a$$

If there be no further losses by deaeration (no residual BOD), then the deficit and the resultant dissolved oxygen will be modified as shown in Table 44.

TABLE 44

Elapsed Time, t, Days	Deficit, Per Cent of Saturation	Dissolved Oxygen, ppm	
		Actual	Increment
0	50	5.4	..
1	28	7.8	2.4
2	16	9.1	1.3
3	9	9.8	0.7
4	5	10.3	0.5
5	3	10.6	0.3

Under the assumed conditions the actual reaeration decreases day by day as the oxygen builds up toward the saturation value, 10.8; that is, the approach to the limiting value becomes slower as the deficit decreases.

Oxygen Requirements. Organic matter, capable of biochemical oxidation (p. 308), utilizes the oxygen of the stream during its stabilization. This is equally true of artificial pollution and of the natural organic pollution of the stream, dead leaves, and the decaying residues of the life of the stream and of its watershed. Thus every stream exists in a state of balance between the oxygen demand of its organic load, on the one side, and the dissolved oxygen content and the rate of reaeration on the other. A more vigorous demand lowers the oxygen concentration and increases the rate of reaeration (by the deficit rule). Even the purest mountain streams are seldom saturated with oxygen, although their oxygen will generally approach saturation values. At the other extreme, heavily polluted streams may carry such excessive oxygen demands as to come into equilibrium with reaeration at very low or even zero oxygen levels.

The Oxygen Balance Sheet. All these facts and relationships may now be brought together and set up as a sort of balance sheet, similar to one which a merchant might set up.

Among the assets one finds *inventory* and *cash on hand,* or, in the present situation, *dissolved oxygen.* As liabilities, there may be listed the ultimate oxygen demand of the organic load, that is, its BOD. A balance taken off at this stage will show one of two conditions:

Assets exceed liabilities, condition solvent.
Assets less than liabilities, condition doubtful.

In the latter situation an accountant seeks further information. He notes that the liabilities are not now due *in toto* but may be paid off at a rate of about 21 per cent of their remaining total each day (the BOD law); that sales and daily income (reaeration) have been regular and continuous and that the management becomes more active, works harder, and does more business as assets dwindle (the deficit law of reaeration). He therefore adds to the assets an item of anticipated income, the rate of reaeration. This again resolves the situation into two possibilities:

Assets plus anticipated income exceed liabilities, condition solvent, but may grow worse temporarily.

Assets plus anticipated income less than liabilities, condition temporarily solvent, but will grow progressively worse approaching insolvency.

One now inquires how long and to what extent will the continued deterioration of the stream continue; or how long will it be before it reaches a level of zero oxygen at which point the major nuisance of anaerobic conditions will be reached?

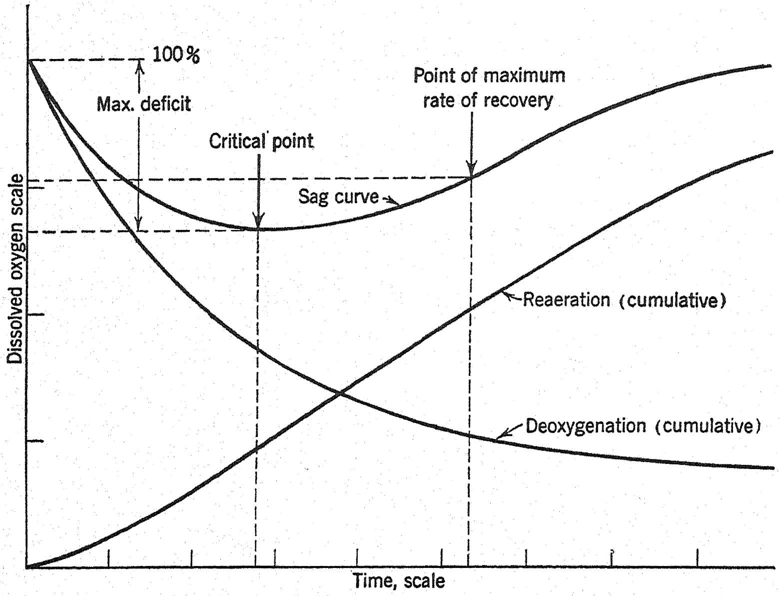

Fig. 70. Deoxygenation, reaeration, and sag curve.

The Sag Curve. This introduces the time relations of the deoxygenation, or BOD reaction, and of reaeration. When the anticipated balance is forecast into the future, it is possible to derive what is known as the *sag curve,* Figure 70. In a qualitative manner it is rather easy to visualize the conditions as they change progressively downstream.

Suppose a stream, at a temperature of 20 degrees centigrade and practically saturated with D. O. at the start, receives a definite BOD load. The curve of deoxygenation will be the curve of the BOD reaction progressing toward its own ultimate completion at a rate of about 21 per cent of its residual value during any one day. It starts off, therefore, at a maximum rate and diminishes gradually and continuously toward zero. Its cumulative value is plotted on the D. O. scale, starting at the initial D. O. value. In the absence of reaeration, this descending curve would be the curve of the residual D. O.

Similarly, reaeration is zero at the start, complete saturation having been postulated. It increases as the deficit increases. Obviously, with a decreasing demand and increasing rate of reaeration, a point will be reached downstream (measured in days of transit, not in miles) at which the two opposing reactions will balance. This represents the lowest point to which the D. O. will be depleted. It is known as the *critical point.* Beyond the critical point, reaeration assumes control, and the condition improves and approaches ultimate saturation, assuming, of course, no additional pollutional load.

The complete determination of the sag curve in any given situation involves a knowledge of the BOD load and of the reaeration constant of the river stretch involved. This latter, as has been indicated, is a function of many physical conditions: depth, velocity and slope, and character of the river bottom. Except in very complete stream studies it is not determinable. For our present purposes it is sufficient to recognize the basic principles involved in sag curve analysis, and its application in a river survey, in the determination of the coordinates of the critical point, its time downstream and its oxygen level, from laboratory examinations.

EFFECT OF SLUDGE DEPOSITS. The deposit of suspended solids in the form of sludge banks just below sewer outlets tends to concentrate the total oxygen demand within a more limited zone than would otherwise be the case. The immediate effect of this concentration is to make the situation worse at or just below the point of deposit, but the net effect upon the oxygen balance of the stream is beneficial.

In the first place, because the effect is concentrated rather than spread out downstream, a greater oxygen deficit is developed at an earlier time, and reaeration, always proportional to the deficit, is augmented; and the removal of some of the pollution from the flowing stream is the equivalent of a partial purification treatment above, which reduces the load upon the lower stream proportionately.

Furthermore, under the conditions of *benthal decomposition*—a term suggested by Fair* to describe this situation—a considerable proportion of the normal BOD load is never developed. Thus, it

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* G. M. Fair, E. W. Moore, and H. A. Thomas, *Sewage Works J.*, **13**, 270, 756, 1209, 1941.

was found experimentally that in a sludge layer about 4 inches in depth kept under observation for 450 days the following disposal was accomplished, values being expressed in terms of per cent of the initial BOD of the material:

Actual benthal demand upon the stream	20.4
Oxidizable ammonia lost	17.4
Oxidizable methane and hydrogen lost	42.3
Residual demand	19.9
Total	100.0
Estimated ultimate residual	16.7

After 450 days, the actual demand exerted upon the stream had amounted to 20.4 per cent of the total, or almost exactly the demand exerted in the flowing load during the first day. There was also a loss of ammonia, which would presumably be later oxidized in the stream and so does not represent a benefit. But the loss of the combustible gases, methane (CH_4) and hydrogen, represents a net saving as these pass out of the system in unoxidized form. There was a residual demand amounting to 19.9 per cent of the initial value, but it was estimated from the rate at which the benthal reaction was proceeding that this would never be reduced below 16.7 per cent. Thus, the stream is definitely benefited by the deposition of this material upon the bottom, to the extent of the ultimate residual 16.7 per cent, which will never be oxidized, and by the methane and hydrogen values lost, a total of 59 per cent.

EFFECT OF TEMPERATURE. Higher temperature speeds up the BOD reaction (Table 38), whereas it decreases the solubility of oxygen (Table 34). Less oxygen is available in warm waters to satisfy a greater rate of demand.

The effect of these relations upon the sag curve is obvious. The critical time is shortened and the critical level of D. O. depressed. A worse condition develops at an earlier time (farther upstream). Thus, warm weather conditions are always worse at points near the source of pollution.

But, by the same reasoning that was applied to the effect of sludge deposits, the effect of warm weather is to concentrate the burden in the upper zone, to increase the rate of reaeration, and to improve conditions farther downstream.

It may also be seen that, with gradually increasing pollutional loads from year to year, such as are commonly met with in stream pollution, early evidence of a coming breakdown will be observed at the summer critical point and during the warmer weather. Further increments of pollution will move the critical point upstream and down the oxygen scale, from year to year.

PLANNING FOR POLLUTION ABATEMENT

Repeated or Multiple Pollution. The preceding discussion of oxygen balance considers a simple sag curve below a single point of pollution. This is seldom the situation. In actual practice, and particularly in the highly developed drainage areas, a river receives discharges from many outlets of cities and industries distributed along its banks, which distort the normal sag curve and complicate the problem of analysis. However, the basic factors of deaeration and reaeration are applicable, and, by considering each stretch of the river from point to point of pollution, taking into consideration the remaining unpaid residual debt from points above, a composite sag curve can be developed.

The combined deaeration liabilities are readily determined by a graphical integration* of individual pollution loads contributed along the river, showing the combined unpaid debt remaining at any location, as well as the debts which must be paid by each stretch of the river between points of pollution (Figure 71). Such an integration also affords a convenient means of determining the relative responsibility of pollutors and the load each individual contributor leaves as an unpaid residual at the doorstep of his neighbor downstream.

Corresponding reaeration assets can likewise be computed for each river stretch and the balance of assets and liabilities determined, to establish a resultant D. O. sag curve for given pollution loads and river runoff (Figure 72).

Oxygen Balance and Drought Flows. Stream runoff and seasonal temperature influence both deaeration and reaeration; consequently, the sag curve will vary widely throughout the year and from year to year. As runoff diminishes, the oxygen sag is steeper and lower. The sag curve, to have full significance, therefore, must be related to the probabilities of drought flow (p. 265). Each drought flow with a given pollution load will produce its own par-

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* The technique of graphical solution of stream pollution problems is more fully described in the author's *Stream Sanitation.*

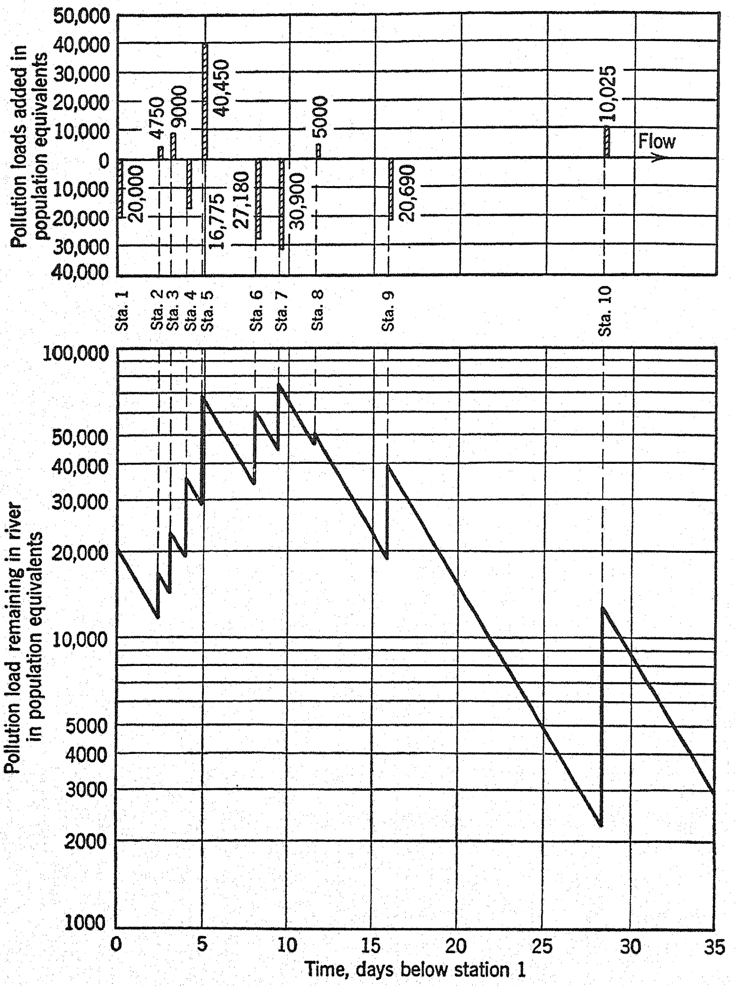


FIG. 71.

A Schematic Plan view showing points of pollution and time of passage at 0.24 cfs/sq mi.

B Integration of pollution load at runoff of 0.24 cfs/sq mi, temperature 20° C.

Drought frequency once in 10 years, minimum monthly average.

ticular D. O. sag curve, and, hence, in turn, each sag curve will have a corresponding probability of occurrence. It is obvious, therefore, that the sag curves must be considered and judged by their frequency of occurrence.

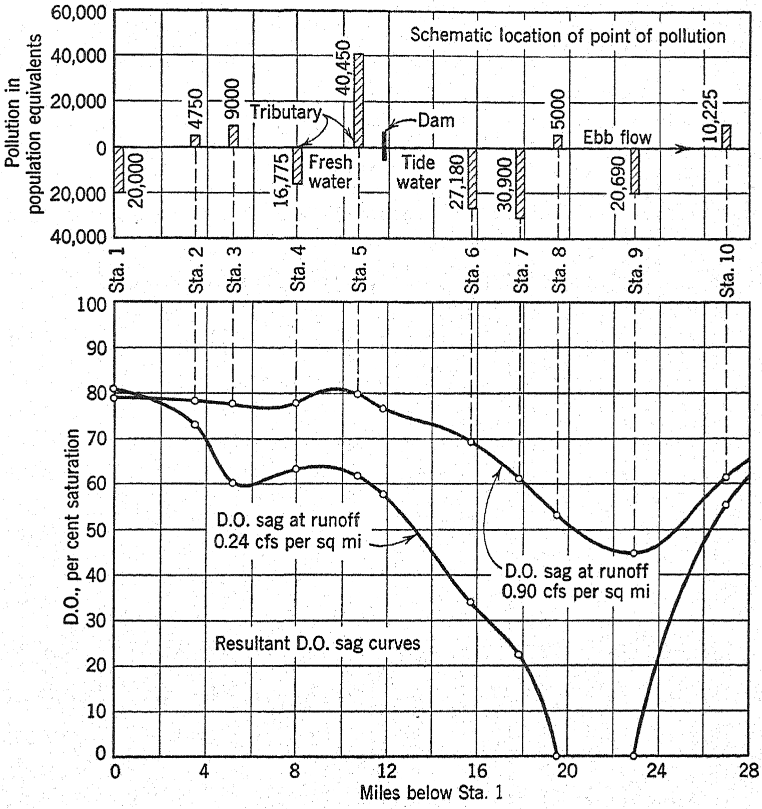


FIG. 72. Relation between D. O. sag curves and runoff. Summer conditions without treatment.

THE STREAM SANITATION PROGRAM

BASIC POLICIES. In the planning of a stream-pollution abatement program, two basic policies must be established: the determination of anticipated water uses and the quality tolerances required for such uses; and the relation of these intended uses to the probabilities of drought flows. Decision as to these two policies must include, in addition to technical determinations, consideration of practical economic factors. It is not economically feasible to provide treatment which insures the desired stream conditions during drought flows of such rarity of occurrence as once in 100 years. On the other hand, it would be economic waste to provide such limited treatment that the stream would degenerate below desired utility levels every year or two. The practical solution lies between these extremes. In general, protection against drought flows of occurrence once in 5 or once in 10 years provides the maximum return consistent with reasonable water use.

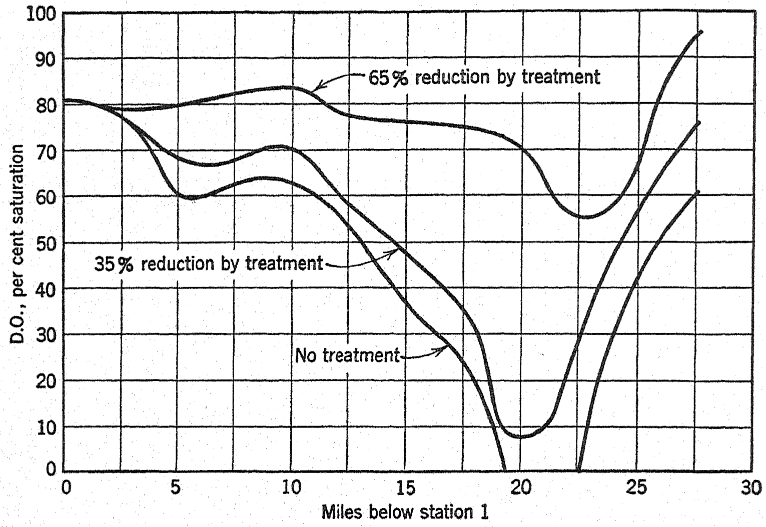


Fig. 73. Effect of treatment on D. O. sag curve at runoff of 0.24 cfs/sq mi. Frequency once in 10 years.

Treatment Required. Once the quality of water required for intended uses and the frequency of drought flow at which such quality shall be maintained have been determined, the degree of treatment required for such quality and runoff is indicated by sag curves computed under various assumed reductions in pollution load. For the example cited, if it is desired to maintain dissolved oxygen above 50 per cent of saturation at a drought flow which will not occur more often than once in 10 years, it is apparent from Figure

73 that a 65 per cent reduction in load would be required. These fundamental analyses form the basis of sound and economical design, taking full advantage of the natural self-purification capacity of each particular stream.

Integration and Coordination. With the establishment of policies and the determination of the degree of treatment required (the diagnostic elements of the problem), the engineer is now equipped with the data upon which he may proceed with the practical planning of a specific pollution abatement program, the curative treatment. In the development of such a plan, three fundamentals should be observed:

Simultaneous consideration of all pollution, industrial as well as municipal.

Integration among municipalities and industries for joint projects on the basis of logical service areas, wherever feasible.

Coordinated action on each stream by drainage basins as a whole.

Industrial wastes and municipal sewage are not mutually exclusive. Much industrial waste can advantageously be combined with municipal sewage for treatment together at the municipal works.

Four avenues of approach to industrial waste disposal have successfully been utilized and are set forth in the order in which they should be applied:

1. Systematic study by the industries of the various industrial processes with a view to the reduction of the volume or strength of the wastes or to their elimination, with possible salvage of products of value.
2. Integration into the municipal system and treatment with the municipal sewage of those wastes which cannot be eliminated and which are inevitable by-products of industrial activity.
3. Preliminary treatment at the industrial plant, prior to discharge into the municipal sewerage system, and disposal through the municipal treatment works, where indicated by economies or technicalities of operation such as detention for regulated discharge, neutralization, or removal of excessive suspended matter.
4. Separate treatment provided at the site of the industry if, owing to remoteness or the nature of the waste, it cannot be economically handled at the municipal works.

The second fundamental is integrated action by logical service areas, based on natural drainage districts rather than on strictly political boundary lines of individual municipalities. This cooperative approach among municipalities is particularly needed in highly industrialized areas surrounding metropolitan districts comprising a patchwork of small political units, each of which cuts across natural drainage districts and, in the majority of instances, is too small to handle its problem independently.

Finally, if the benefits of pollution abatement are to be fully realized, it is essential that action be coordinated by drainage basins as a whole. This necessitates a unified program, with logical scheduling of treatment works construction along the entire river. A haphazard program, where several build, while other intervening communities continue to discharge untreated wastes, obviously is economically unsound and will fail to achieve the objective of stream improvement.

TERTIARY USES OF WATER

Among the tertiary uses of water, bathing and shellfish culture present public health problems of major concern. The relation of polluted waters to oysters, clams, and other commercial shellfish is primarily a matter of food control and is dealt with in Vol. II. The public health aspects of bathing beaches and swimming are not limited to the water contact, but, in view of the paramount importance of water quality in these sports, it is appropriate and convenient to include the entire subject of bathing under the tertiary uses of water.

BATHING

Benefits and Public Health Hazards. Swimming and recreation at the seashore or in the waters of the lake or stream are of *positive health value,* particularly to the confined city dweller. Unfortunately, the value of these health assets has not always been fully recognized; many excellent beaches and recreational areas, particularly in the larger metropolitan districts, where they are most needed, have been rendered useless by sewage pollution. This condition has driven the city dweller farther and farther from home in his instinctive search for a place to relax at the water's edge. Time and expense of transportation to distant areas and the excessive crowding at remaining near-by beaches are factors inhibiting full and universal participation in this healthful recreation. The demand for decent safe bathing places has also led to the increasing use of public swimming pools in the cities.

Associated with the positive health values there are also certain health hazards. These fall into three categories: contagious diseases and infections through direct water contact; infections through contact with auxiliary facilities (floors and walls of dressing rooms, bathing suits, and towels); and accidents.

Disease transmission through direct water contact differs in several respects from that associated with domestic water. Less water is swallowed so that the widespread epidemics of intestinal diseases brought about by a relatively slight contamination of drinking water are contrasted here to only sporadic cases. Contact is more prolonged, often associated with fatigue or chill, and diving forces bacteria already present deeper into the ear and nasal passages. Irritation of the mucous membranes and the skin may result from excessive concentrations of chemicals remaining after water treatment. Opportunity for disease transmission through other contacts is also greater than in normal situations because of dressing and undressing in the close quarters of the dressing room used by many persons, and of the moist condition of the skin. The common skin infection, athlete's foot is a familiar illustration.

BATHING PLACES. It will be convenient to study bathing places under three groups distinguished by water sources, layout, and operational features.

At *natural beaches* water quality is maintained by replacement through stream flow, circulation, or tidal action. *Seminatural outdoor pools* or *ponds* are bathing areas that have been created by impounding a small stream or improving a pond. Water quality may be under a certain measure of artificial control. *Swimming pools* are wholly artificial structures in which replacement of water is reduced to a minimum and quality control is by means of recirculation and treatment.

The classification of health hazards into infections due to water contact, those due to out-of-water contact, and accidents provides a logical outline for the discussion of bathing beach sanitation.

CONTROL OF BATHING WATER QUALITY

Quality standards for bathing waters are discussed in chapter 9 (p. 322). In *natural bathing places* control over quality extends far beyond the immediate area and involves broad policies with respect to community sewage treatment and preferential uses of natural waters. Bathing beaches must be located at *safe* distances from sewer outfalls, but no arbitrary rule as to time and distance can be justified. The extent of sewage treatment, its dilution ratio in the stream, the direction and tidal variations of the flow, temperature and the opportunities for self-purification, all enter the problem. A detailed study of the physical factors, together with actual bacteriological studies of the bathing area provide a basis for judgment. Even so, as indicated under the discussion of standards, this judgment is more likely to be based upon the rule of expediency than upon any satisfactory epidemiological evidence.

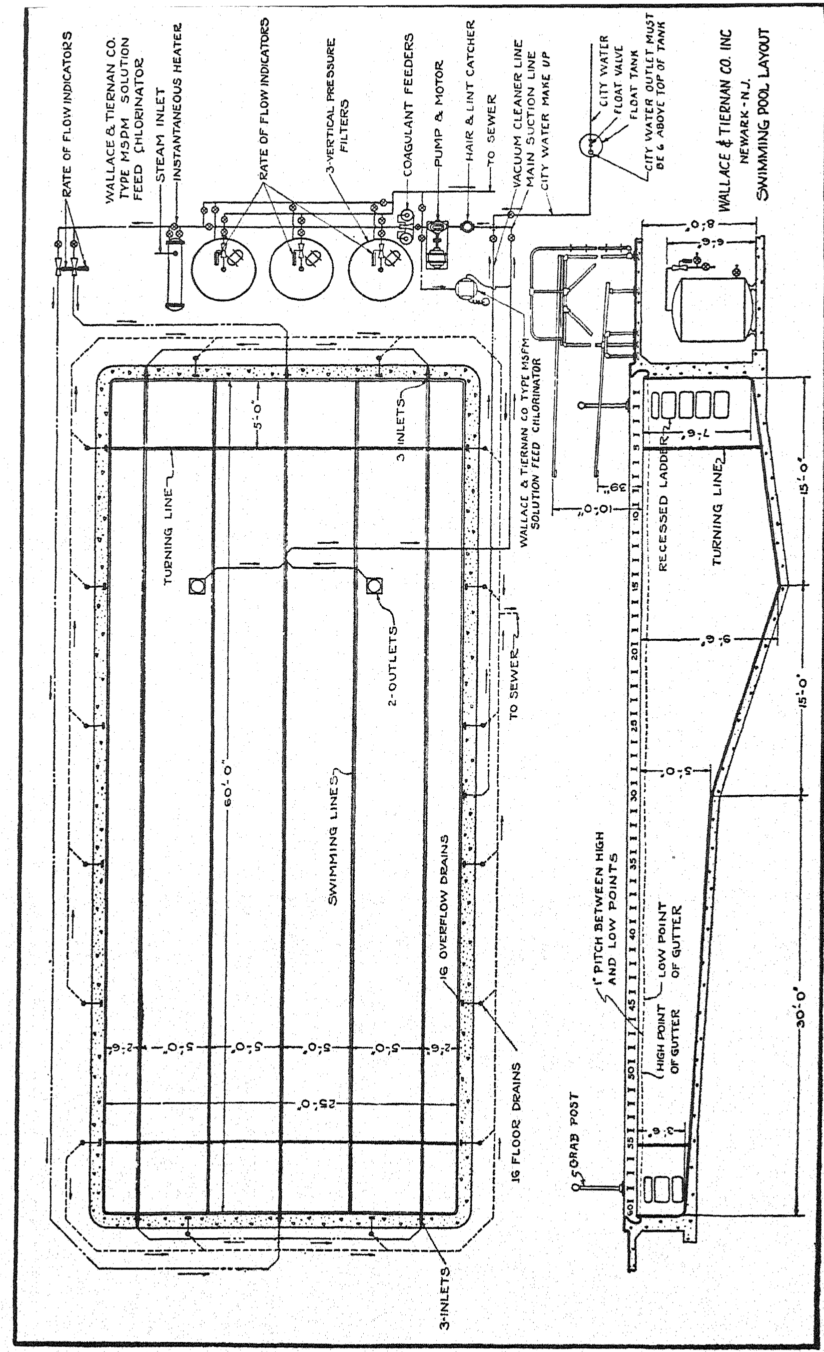
Perhaps the only routine operational control measure which can be exercised to influence water quality is regulation of the number of bathers. Many times bathing areas, otherwise satisfactory, become unduly polluted as a result of overcrowding.

The *seminatural pools* likewise depend upon a natural flow of water of satisfactory quality. To the extent that some of this flow may be diverted for treatment and recirculation, or the natural flow may be treated *in toto,* the conditions here merge with those of swimming pools.

It is more difficult and more hazardous, however, to treat a dangerously polluted stream continuously than to maintain high quality in a self-contained pool by recirculation. If a flowing source is utilized, its quality should be reasonably satisfactory at the outset.

In the *swimming pool* water is drawn initially from a potable source, usually a domestic supply, and is continuously reused with only small additions to compensate for losses. The maintenance of quality depends upon three operational features: treatment facilities; recirculation and distribution system; and regulation of bathing load. Figure 74 shows the layout of a typical artificial pool of which Figure 75 is a simplified flow diagram.

In supplying the pool from a potable source, either initially, or periodically for make-up water, an important sanitary precaution must be emphasized. There should be no direct connection at any point between the piping system of the pool and that of the potable supply. Water is admitted to the pool directly (or to a small supply tank connected to the suction line of the pump) through an independent overhead supply line, terminating at least one foot above the overflow line or rim of the pool or tank. This precludes any



Courtesy of Wallace and Tiernan Co.

possibility of backflow or back siphonage of pool water into the potable supply lines.

The water is continuously recirculated and treated. It is drawn from the bathing area at one or more points, usually from the deep end of the pool, passed through a hair and lint catcher and filtered in a rapid sand filter of the pressure type. It may then be passed through a heater after which it is disinfected. The treated water is distributed through multiple inlets, so as to insure as uniform a distribution as possible. The two major principles associated with the treatment of bathing waters are *clarification* (accomplished by

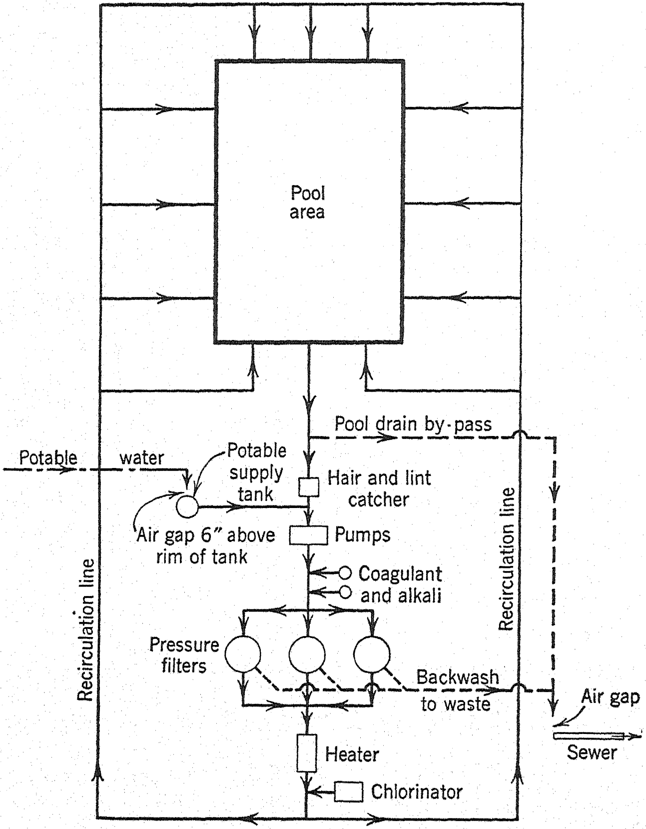


Fig. 75. Schematic layout of pool-water treatment and recirculation system.

mechanical means) and *disinfection*. These principles are discussed in chapter 13 and their application to water supply, in chapter 14. Specific applications associated with bathing waters are briefly touched upon here.

FILTRATION. It is recommended* that the filters should have a daily capacity equal to at least two and preferably three times the pool volume, in order to maintain clarity. This capacity is divided into at least two filter units. The treatment system is kept in operation when the pool is in use and for additional periods, if required to maintain water quality.

The clarity of water desirable is beyond that measurable by usual turbidity and color determinations. A practical operating test of satisfactory clarity is the ability to see distinctly a black disk 6 inches in diameter on a white field placed on the bottom of the pool at the deepest point, 10 feet out from the side wall and viewed from the side of the pool at a distance of 30 feet in fresh water or 15 feet in salt water.

Figure 76 shows a cross section of a typical pressure filter. It is similar to the conventional rapid sand filter (p. 515) except that it is housed in a pressure-tight container, thus permitting it to be inserted in the pressure discharge line of the pumps. The pressure filter is equipped with chemical solution pots for the introduction of alkalinity (usually soda ash) and a coagulant (alum). These chemicals are drawn directly into the inlet line of the filter, and, thus, the usual flocculation and sedimentation operations employed in the treatment of potable water supply are not provided for.

This feature of the treatment system of pool waters may lead to considerable operating difficulty. Where excessive amounts of coagulant are introduced, the alum in solution passes through the filter, forms floc within the pool, and imparts, rather than removes, turbidity. This can be avoided by using smaller doses of coagulant, operating intermittently without coagulant or providing auxiliary coagulation and sedimentation units. The filters are cleaned once or twice weekly by backwashing similar to the method used for conventional rapid filters. The backwash water is discharged to the sewerage system.

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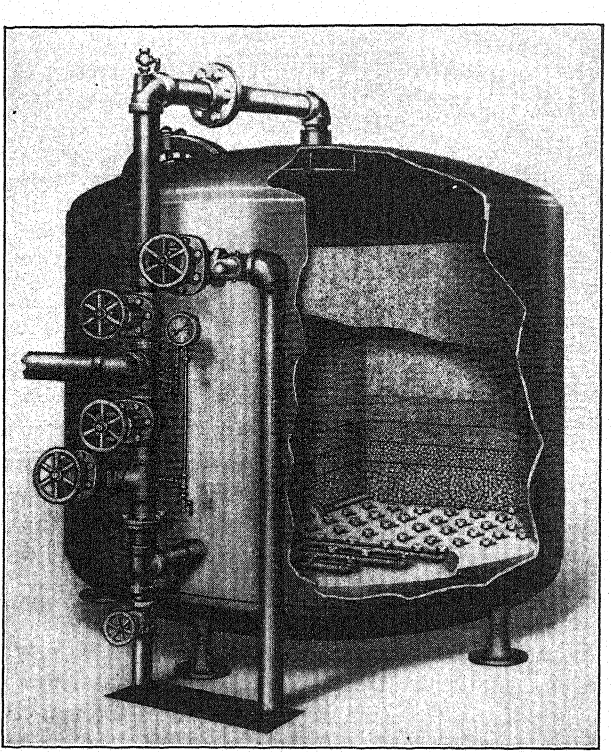
* In what follows we are guided largely by the recommendations of a Joint Committee of the American Public Health Association and the Conference of State Sanitary Engineers in their *Recommended Practices* (see reference at end of chapter).

Here, again, a sanitary precaution is to be emphasized. There should be no direct connection at any point between the piping system of the pool and drainage lines connected to plumbing or sewerage systems. Backwash waste lines, drains for emptying the pool, scum gutter, or other drains discharging to waste must be separated from the sewerage system by an air gap, to prevent any possibility of backflow or back siphonage into the pool water.



Courtesy of International Filter Co.

Fig. 76. Pressure filter.

Disinfection. Disinfection of bathing waters is conducted so as to provide a residual effect in the water at all times and throughout the pool. This is for the purpose of reducing to a minimum local contamination of intestinal or respiratory origin. This feature is so important that only disinfectants, such as the chlorine compounds, capable of providing this residual action are acceptable.

When chlorine is used, the residual shown by the ortho-tolidine test* should be not less than 0.4 nor more than 0.6 part per million. Excessive residuals give rise to objectionable odors and irritation of the skin and mucous membranes.† If chlorine and ammonia are used, these objectionable features are minimized. The disinfection rate is slower, and higher residuals, between 0.7 and 1.0 part per million, are necessary and permissible. Acidity is likely to cause irritation of the eyes, and it contributes to the irritating effect of the chlorine residual. The *p*H of the water should be maintained between 7.0 and 7.6.

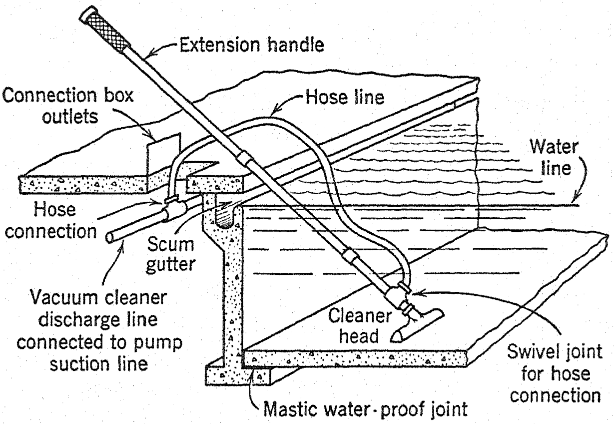


FIG. 77. Pool wall and floor section, showing vacuum-cleaner arrangement.

OTHER CONTROL MEASURES. In addition to treatment works there are certain auxiliary devices needed to protect against water contamination. *Scum gutters* are installed peripherally at the water level to provide a receptacle into which bathers may expectorate and to receive surface overflow. The scum gutters are normally connected to the pump suction and thus serve also as a circumferential outlet from the pool to the water treatment system.

Floor drains are installed in the walkways surrounding the pool to intercept drainage which might otherwise enter the pool. In some

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* See p. 479 (footnote).

† Recent studies have indicated that, where the breakpoint method of chlorination is employed, higher free chlorine residuals may be held without objection or complaint and with improved results.

installations they are connected to the scum gutters. A so-called *vacuum cleaner* (Figure 77) is provided for removing deposits from the pool floor. It is best employed after several hours of quiescence. The discharge line is connected to the pump suction.

The *bathing load* has a direct relation to water quality since the bathers are the major source of pollution. A heavy bathing load likewise increases the opportunities for disease transmission by direct contact. An allowance per bather of 27 square feet in the deep water area used for swimming (exclusive of areas reserved for diving) and of 10 square feet in the shallow area for nonswimmers, is recommended. These limitations are highly desirable, but few regulatory agencies prescribe them, relying for control primarily upon the requirements of water quality.

CONTROL OF AUXILIARY FACILITIES

Certain onshore auxiliary facilities are essential to the satisfactory operation of both natural beaches and artificial pools. These facilities are generally referred to as bathhouse accommodations, including dressing rooms, lockers, showers, and toilets.

Dressing rooms of sanitary construction must be provided to accommodate the maximum number of bathers, with separate quarters for men and women. Walls, ceilings, and floors of impervious material free of cracks and open joints so arranged as to facilitate cleaning are essential. Likewise, furniture and lockers are of simple design and installed in a manner to permit flushing and cleaning without accumulations. The general layout should insure separation of bathers from spectators.

Lavatories, toilets, and showers are located to facilitate their use prior to entrance to the bathing area, with toilets preceding showers. Recommended number of units are as follows:

One lavatory adjacent toilets for each	150 lockers.
One toilet (women) for each	80 lockers.
One toilet, one urinal (men) for each	100 lockers.
One shower for each	80 lockers.

Showers, to be effective, must provide soap, warm water, automatic regulation to prevent scalding, and side spray to avoid unnecessary wetting of the hair. These facilities must be connected to the municipal sewerage system or provided with a satisfactory separate treatment and disposal works, so located as to preclude possibility of contamination of the bathing area.

Sanitary drinking fountains are installed both in the bathhouse and adjacent the bathing area for convenient use. If municipal water supply is not available, precautions must be taken to insure a safe well supply.

Heating, lighting, and ventilation are important to the proper maintenance of bathhouses and indoor pool enclosures. The temperature of the pool water should be at or above 75 degrees Fahrenheit, and should not be allowed to fall more than 2 degrees below the room temperature.

Foot baths commonly placed at the entrance to bathing areas for the purpose of preventing spread of athlete's foot are of questionable value. If installed, they must be cleaned daily and the concentration of disinfection agent maintained. Foot baths are no substitute for routine examination of bathers for open infections, frequent and thorough cleaning and disinfection of walkways, and the use of paper slippers.

Bathing suits and *towels* are an essential auxiliary facility of primary importance. After each individual use, suits and towels must be washed in hot soapy water, rinsed for a period of at least one minute in clean water at 200 degrees Fahrenheit and thoroughly dried before re-use. Toilet articles which might come into common use among bathers obviously must be prohibited.

Supervision of the bathing establishment is essential, and, unless adequately staffed and maintained, the best of auxiliary facilities can degenerate to serious health hazards.

ACCIDENT PREVENTION

In the construction of bathing facilities, attention should be given to accident prevention, both in the swimming area and in the auxiliary facilities. Nonskid walkways, with avoidance of curbs and stairs, minimize accidents from falls. Artificial pools should be constructed with smooth impervious walls and floors of light color, marked to indicate water depth. There should be no protrusions such as ladders or scum gutter. Sharp vertical drops in the pool bottom are a hazard to nonswimmers and dangerous for submerged swimmers. Diving towers and spring boards must be rigidly constructed and securely anchored to insure stability under the heaviest possible load, with provision of an ample factor of safety against structural failure. Unobstructed headroom above and adequate water depth are important. Excessively high towers are to be discouraged. Fixed or floating platforms should be designed to minimize possibility of entanglement or trapping of bathers beneath the platform. In floating platforms, at least one foot of air space should be provided beneath the platform to safeguard a swimmer temporarily trapped beneath it.

The danger of accidental drowning is an ever-present hazard. No bathing establishment should be opened for use without constant supervision of lifeguards or qualified pool attendants, augmented with readily available lifesaving and first aid equipment. Where possible, segregation of nonswimmers in shallow areas greatly reduces hazards. In any event, clearly marking shallow areas and the provision of surf lines at frequent intervals are essential.

As with hazards of disease and infection transmission, accidents are a function of bathing load and increase with overcrowding. Likewise, accident prevention, to be effective, must be practiced daily under intelligent supervision. The requirement of water clarity in pools is largely a matter of accident prevention; it enables the guard to note any underwater accident or the temporary incapacity of a bather.

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CHAPTER 13

TREATMENT OF POLLUTED WATERS

PRINCIPLES

It has been noted that treatment plays an important role in both the intake and the outgo segments of the water contact cycle: in water supply to reduce harmful and objectionable polluting matter to limiting concentrations or tolerances consistent with intended water uses; in sewage disposal, prior to discharge, to reduce physical, chemical, and bacterial nuisances to levels which, with natural self-purification, will insure maximum utilization of water resources. Certain basic principles are equally applicable to the treatment of polluted waters of both segments, water supply and sewages. We here identify these common principles and deal with the theory of their action, leaving for subsequent chapters their application in practical treatment systems.

CLASSIFICATION OF WATER IMPURITIES FOR TREATMENT

Each of the basic treatment principles deals with a specific type of impurity. It will be helpful, therefore, to classify these impurities according to their physical and other characteristics as related to treatment. As a group, the water impurities are known as *solids.*

TABLE 45

Classification of the Solids in Water

Class	Description
Suspended	Removable by filtration through paper.
Settleable or nonsettleable	Removable (or nonremovable) by quiescent settling in a laboratory jar.
Dispersed	Nonsettleable solids having diameters of 7.0–0.2 micron (somewhat arbitrary)
Colloidal	Will pass a Seitz filter (diameter less than 0.2 micron) but not in true solution.
Dissolved	True solution. Dialyzable.
Bacteria and other organisms	Living.

THE SIX BASIC PRINCIPLES

In examining the art of treatment with a view to classifying practice on the basis of fundamental principles, we are able to segregate six general categories, namely:

Mechanical separation.
Hydraulic separation.
Chemical coagulation.
Chemical and physical reaction.
Disinfection.
Biological reaction.

We identify these principles by the end results rather than by any precise understanding of how these results are brought about. The art of treatment has been developed, to a large extent, by cut-and-try experimentation rather than by the application of known scientific principles. Furthermore, our concept of principles changes as new knowledge better defines the modes of action. The principles discussed here, therefore, must be judged in this light; they are presented as expressions of common understanding of the art at this time and in the present stage of its development.

Mechanical principles are limited to the removal or separation of suspended matter by purely mechanical means, such as screening or straining. *Hydraulic separation* is effective only in the removal of suspended matter, which, being heavier or lighter than water, will, under proper conditions, deposit on the bottom of a tank or rise to the surface, where it can be removed.

The principles of *chemical coagulation* are limited to the removal of colloidal matter and very fine nonsettleable suspended matter bordering on the colloidal state. Matter in true solution is unaffected, and chemical coagulation is inefficient in removal of settleable suspended matter.

The *chemical* principles, as distinct from chemical coagulation, bring about chemical reactions and chemical changes in the dissolved inorganic salts or gases, and the removal by precipitation of such substances as calcium, magnesium, iron and carbon dioxide. They include also the addition of desirable chemical constituents such as fluoride. It is convenient to deal here also with certain physical reactions (aeration, adsorption) associated with and related to some of the chemical reactions employed.

The principle of *disinfection* is applied exclusively to the destruction of living matter, chiefly the bacteria, by means of substances, disinfectants, inimical to their life processes.

The *biological* principles, adaptations of the natural processes of decay, are capable of effectively removing organic polluting matter in all four states, and are the only principles now in use capable of removing dissolved organic matter. These natural processes are *biochemical* processes, as distinguished from the chemical and physical processes. They involve feeding, breathing, growth, reproduction and death in a complex complimentary as well as competitive chain of living forms supported in large measure by the organic pollution of the water.

The principles, thus briefly identified, are now dealt with separately with a more detailed discussion of their modes of action and specific applicability to the general problem of treatment of polluted waters.

MECHANICAL PRINCIPLES

A treatment works is a modern mass production industry, operated continuously 24 hours a day, throughout the year, on the production line layout. The *raw material,* polluted water, enters and is moved continuously through the works from operation to operation, during which materials are added and removed. Finally, the finished product, the *effluent,* leaves the works either to a pipe system as water supply or to a natural watercourse. As in any modern, mass production factory, many devices and operations, purely mechanical in nature, are employed. These mechanical devices and operations may, for convenience, be classified into:

Those which facilitate the continuous flow of the product through the plant.

Those which are adjuncts employed merely to convey materials to the line of flow or to convey materials separated from the line of flow.

Those devices or operations which, in themselves, are employed on the product, either to condition it for other operations or to effect a removal of a portion of polluting material.

The first class includes such mechanical devices as pumps; the second class, devices to feed and control the application of chemicals, or scrapers and skimmers to collect accumulations of settled matter (*sludge*) on the bottom of a tank and floating matter (*scum*) from the water surface. These two classes are the subject matter of hydraulic texts and of the literature of treatment works design. It is the third class of mechanical operations, which are employed on polluted water as conditioning steps or which, in themselves, effect removal of a portion of the pollution load, which are of major concern here. These operations can be further subdivided into *screening, comminuting, straining,* and *vacuum filtration.*

SCREENING. Screening operations consist of intercepting the larger suspended matter by inserting a stationary or moving mechanical device in the line of flow which effects the separation of suspended matter by limiting the size of openings through which polluted water must pass. Material finer than the openings passes through, while the coarser material is retained on the screening device. Removal is, obviously, limited to suspended matter, and the extent of removal is a function of the size of the openings of the sieving or screening device and the velocity at which the flow passes through these openings.

The disposal of the material collected on screening devices will vary, depending upon the nature and quantity of the material removed. The relatively small amount of such material as sticks, branches, and leaves, removed by the coarse racks (3-inch spacings), generally employed on a waterworks intake, presents no problem in disposal. Organic material removed by mechanical screens or fine screens from sewage or industrial wastes cannot so readily be disposed of. The practice in the past has been to collect this material in containers and dispose of it by burial or to transfer it by some such mechanical means as belt conveyor to an incinerator. The difficulties and expense entailed in handling and disposing of screenings has led to the abandonment of the use of fine screens and a change in the theory and practice of mechanical screening.

COMMINUTION. In sewage works practice, today, screening is not regarded as a means of *removing* suspended matter, but rather as a means of *conditioning* the coarser suspended matter so that it will not interfere with treatment apparatus. The intercepted screenings are conveyed to a shredder, ground into fine pieces, and returned to the sewage flow to be removed with other suspended matter in subsequent operations.

Comminuting. A new type of screening device screens and shreds in a single operation. This is termed comminuting. A slotted revolving cylindrical drum is placed in the line of flow; the polluted water passes through the slots; and the suspended matter is retained on the outside of the revolving drum. Cutters attached to the revolving drum impinge the material retained on the drum against a stationary comb until the material is fine enough to pass through the slots.

STRAINING. Straining is defined as a filtering operation wherein the polluted water is passed through a fine porous medium whereby suspended matter is strained out or retained on the filtering mat as the water passes through it. The operation is entirely mechanical and is not carried on in such a manner as to develop biological action. The media usually employed are sand, magnetite, or pulverized coal, retained on a screen or underdrainage system. Polluted water may be passed through the straining medium either from the top downward or from the bottom upward. When the accumulations of the removed material build up to a point where the head loss due to resistance of the flow reaches a limiting point, some type of cleaning device or backwash is employed whereby the filtering medium is thoroughly agitated, and the lighter organic matter accumulated on and in it is flushed off, leaving the heavier medium, cleaned and ready for the next cycle.

The effectiveness of the removal of suspended matter by straining or filtering through a porous medium is dependent principally upon the porosity of the medium (the proportion of its volume that consists of open spaces), the character of the suspended matter to be removed, and the rate of filtration of the polluted water. As filtration continues, the accumulation of the removed suspended matter reduces porosity which increases effectiveness of removal but which also increases the resistance to flow and head loss. These changing conditions complicate the formulation of a useful mathematical expression, without simplifying assumptions. Fair and Hatch* have developed such an expression for flow of clean water through clean sand, a simplified form of which, for sand of uniform porosity, size and shape, is as follows:

$$\frac{h}{d} = \frac{k\mu}{w} \cdot \mathrm{V} \cdot \frac{(1-P)^2}{P^3} \cdot \frac{s^2}{D^2}$$

in which h = the head loss through the sand depth, d; k = a factor ranging from 4 to 5, depending upon the degree of compactness of

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[*] G. M. Fair and L. P. Hatch, *J. Am. Water Works Assoc.*, 25, 1551, 1933.

the bed; μ = the coefficient of viscosity; w = weight of water per unit of volume; V = the rate of filtration, expressed as velocity; s = the shape factor of the sand grains; D = the size of the sand grains; and P = the porosity of the sand.

VACUUM FILTRATION. Vacuum filtration is the operation wherein polluted water containing a high concentration of suspended matter is caused to flow through a mat of its own suspended matter retained on a screen or cloth on the under side of which a partial vacuum is maintained. Usually vacuum filters are cylindrical in form and revolve, only partly immersed in the polluted water. As the submerged section of the cylinder emerges from that position, the internal vacuum continues to extract water from the mat, reducing the fluid mass to a solid cake (⅛ inch to ¼ inch thick) in the course of a single revolution. This principle of separation of suspended matter from polluted water is adaptable to industrial wastes where the concentration of suspended matter is sufficiently high to develop the required mat. Municipal sewage does not permit efficient use of this principle, which is frequently used, however, in dewatering sludge removed from sewage.

HYDRAULIC SEPARATION

Hydraulic separation takes advantage of the difference of the density of substances. Particles heavier than water tend to settle to the bottom, and those lighter tend to rise to the top. The time required for separation, either by settling or rising, is dependent upon the rate at which these particles can move vertically in a water medium. Hydraulic separation will be considered in the two phases, sedimentation and flotation.

PHYSICAL PRINCIPLES

An excellent compendium of the principles of sedimentation, by Camp* has been freely drawn upon in the following discussion.

A spherical particle, released in a quiescent fluid medium, will accelerate until the frictional resistance or drag of the fluid equals the impelling force. Acceleration then ceases, and the particle subsides at a uniform rate. Two major drag forces are at play, inertia

* T. R. Camp, *Proc. ASCE,* 71, no. 4, 445, April 1945.

and viscosity. Newton assumed that the drag force was a function only of inertia whereas Stokes emphasized the role of viscosity.

The impelling force F_i is the weight of the particle in the liquid medium, or

$$F_i = (\rho_s - \rho)gV \qquad (1)$$

in which ρ_s and ρ are the respective densities of the particle and of the fluid, g the acceleration of gravity, and V the particle volume (for the sphere, $\pi d^3/6$). Newton defined the drag force F_d by the relation:

$$F_d = C_d A \frac{\rho v^2}{2} \qquad (2)$$

in which p_s and p are the respective densities of the particle and of velocity of movement through the fluid, and A the projected area (for the sphere, $\pi d^2/4$). Equating (1) and (2), the subsidence velocity is obtained as

$$v = \sqrt{\frac{4}{3} \cdot \frac{g}{C_d} \cdot \frac{(\rho_s - \rho)}{\rho} \cdot d} \qquad (3)$$

Stokes defines the drag force by the relation:

$$F_d = 3\pi\mu d v \qquad (4)$$

in which μ is the absolute viscosity of the medium. Equated with (1), this gives for the velocity,

$$v = \frac{1}{18} \cdot \frac{(\rho_s - \rho)g}{\mu} \cdot d^2 \qquad (5)$$

which is Stokes' law.

Combining (4) and (2) reveals that, for truly viscous settling, Newton's coefficient of drag C_d becomes

$$24 \div \frac{d\rho v}{\mu} = \frac{24}{R}$$

R being Reynolds number, defined in the terminology used here as $d\rho v/\mu$.

It has now been verified by many careful experiments that both viscosity and inertia are involved for the range of suspended matter contained in polluted water and that the drag force or resistance to subsidence depends upon their relative influence. The ratio of inertia force to viscous force is known as Reynolds number R.

Where the ratio is small, viscosity dominates, and subsidence follows Stokes' law, with velocity inversely proportional to viscosity. Where the ratio of inertia to viscosity is high, inertia force dominates and velocity follows Newton's law. Between the low-velocity viscous settling and the high-velocity turbulent inertia settling lies a transition range in which, as velocity of subsidence increases, the influence of viscosity decreases, and, as velocity of subsidence decreases, the influence of viscosity increases.

The relationships of these forces to subsidence velocities of spheres are shown graphically in Figure 78. Curve A shows the relationship between coefficient of drag (C_d), determined experimentally by a number of independent workers, and the proportion of inertia to viscous force at play, namely, Reynolds number R. Curves B_1 and B_2 relate subsidence velocity to diameter for spheres of density 2.65, in water at 10 and 20 degrees centigrade, respectively. Curves C_1 and C_2 are similar for density 1.2. Curve A indicates that the log of C_d varies linearly with log R for values of R less than 0.6. This is the region of viscous settling. For values of R over 2000, C_d is constant at 0.4 (as assumed by Newton). This is the region of turbulent settling. Between these limits the relation between C_d and R is variable.

In the region of viscous settling Stokes' law is valid; the velocity of settling varies inversely as viscosity and directly as the square of the diameter and as the difference in density, equation (5). This is the region of small spheres and low-velocity settling. Viscosity, as indicated in Figure 78, is a temperature function. Referred to 50 degrees Fahrenheit as a standard, it varies approximately as $60/(T + 10)$.

On the other extreme, turbulent settling, viscosity is no longer an influence (the differences in subsidence rate due to temperature and hence, viscosity, converge to a common line); subsidence varies as the square root of the difference in specific gravity between the particles and the liquid medium and as the square root of the diameter of spheres, equation (3). This is a region of high velocity and spheres of larger diameter.

In the transition region the ratios which define the relationships for the two extremes do not apply, and subsidence velocity in relation to size of particle must be determined directly from the B and C curves (or others, similarly constructed) or computed from the basic equations.

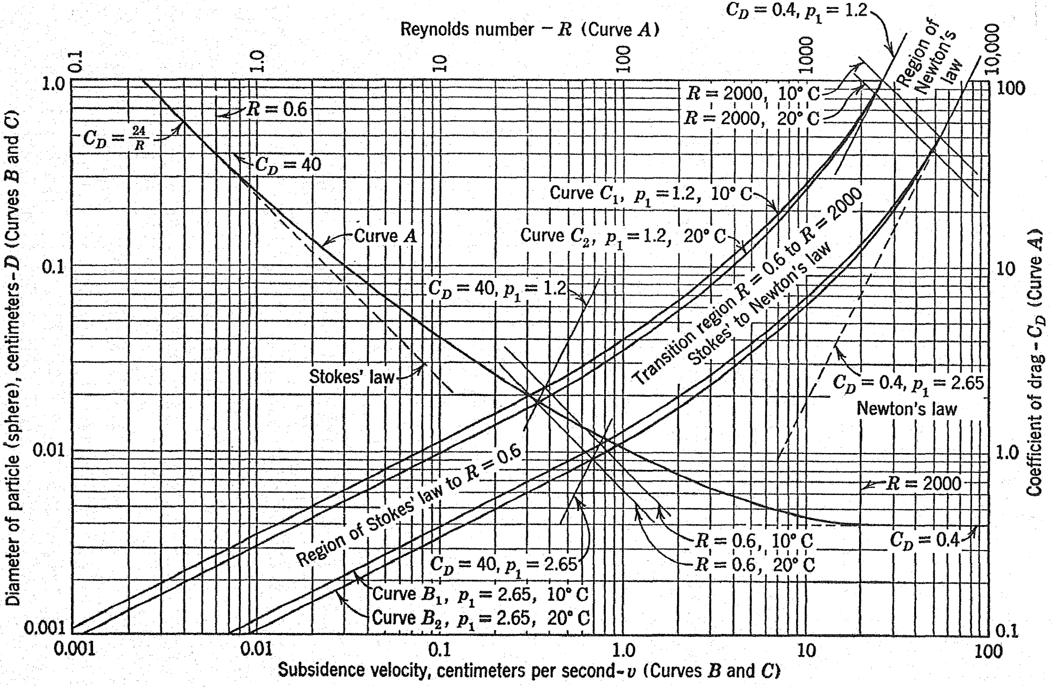

FIG. 78. Relation between coefficient of drag and Reynolds number, and diameter of spheres and subsidence velocity in water.

DIFFERENTIAL SEDIMENTATION OF GRIT. Differential separation of suspended matter can be accomplished not only between that which floats and that which sinks, but also among the suspended particles that settle. In practical treatment, it is desirable to separate inert mineral grit, sand, and cinders, of a density of 2.65 and down to a size of approximately 0.2 millimeters, from the organic matter. Such a separation is feasible because of the distinctly different subsidence characteristics of these two classes of material. Referring to Figure 78, curve B_2, we note that a particle, approximately spherical in shape and having a density of 2.65, would settle in water at 20 degrees centigrade at a rate of 2.5 centimeters or about 0.08 foot per second. Such a particle would be deposited on the bottom of a grit channel 4 feet deep in 50 seconds. A particle of organic matter (density 1.2) of the same size, curve C_2, would have a subsidence velocity of only 0.42 centimeter per second, approximately one-sixth of that of the sand particle, and would require six times as long to reach the bottom of the 4-foot channel. If the detention period of the grit chamber is set at 50 seconds, all mineral grit of 0.2 millimeter in size or greater will be deposited, and most of the organic matter of 0.2 millimeter or less will be carried through the chamber. Organic particles of 0.7 millimeter would have a subsidence velocity just equal to that of mineral grit of 0.2 millimeter, and, therefore, if the organic matter were granular, particles 0.7 millimeter or larger in size would also be deposited. Two additional factors aid in the differential separation of grit from organics. The organic suspended matter is generally flocculent rather than granular, and it has a tendency to absorb water, which lowers its density below 1.2.

BOTTOM SCOUR. The second factor relates to bottom scour caused by the tractive force of the water moving through the grit chamber. By regulating the critical velocity, bottom scour action can be employed as a *differential washer,* leaving the inert mineral deposits but flushing out the lighter organic matter from the deposit. From extensive studies by Shields,* the critical velocity required to bring about the desired differential scour action can be determined from the following equation:

$$V_c = \sqrt{\frac{8B}{f} \cdot g \cdot (S - 1) \cdot d} \qquad (6)$$

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* Shields, contained in *An Analysis of Sediment Transportation in the Light of Fluid Turbulence,* by H. Rouse, *U. S. Dept. Agr.,* Sedimentation Division, 1939.

or

$$d = V_c^2 \frac{f}{8Bg} \cdot \frac{1}{(S-1)} \tag{7}$$

in which V_c is the critical velocity at which scour will commence; g the acceleration of gravity; f the Weisbach–Darcy *friction factor,* which may be taken at about 0.03 for grit chambers; B an experimental constant, the value of which is about 0.04 for unigranular material, and, for nonuniform and sticky material like grit, about 0.06; S the specific gravity of the particle; and d its diameter.

The critical velocity below which 0.2 millimeter sand grains, 2.65 specific gravity, would remain deposited is thus obtained from equation (6) as 0.75 feet per second. From equation (7) it may be seen that for any given velocity the diameter of the particle which would be scoured out varies inversely with the difference in specific gravity of the particle and that of water. An organic particle, specific gravity 1.2, just capable of resisting scour, would be larger than a mineral particle, specific gravity 2.65, similarly unaffected, in the ratio $(2.65 - 1)/(1.2 - 1) = 8.25$. At a velocity of 0.75 foot per second, which would just retain 0.2 millimeter sand, organic matter of specific gravity 1.2 and smaller than 1.65 millimeter, or of specific gravity 1.1 and smaller than 3.3 millimeter, would be scoured out.

These principles involving relative subsidence velocities and relative tendencies to scour are the basis of modern design in hydraulic separation of inert from organic materials in the treatment of polluted waters.

SEDIMENTATION OF FLOCCULENT SUSPENDED MATTER

In the preceding discussion of differential separation of grit, the subsidence velocities developed related to granular discrete particles approaching spherical shape. Much of the suspended organic matter in polluted water is *flocculent* in character, that is, shaped more like snowflakes than like granular pebbles. Although basically such flocculent particles are influenced by the same forces impelling sedimentation, characteristics of subsidence of such particles are modified by other factors.

A crude idea of the differences in character of subsidence caused by shape of a particle can be gained from the fall of two pieces of paper, one rolled into a small wad and the other left as a sheet. If these are allowed to drop from some height through quiescent air, the wad will descend in a definite path at a definite rate, whereas the sheet will dart about, alternately diving down vertically on edge, then flattening out, perhaps horizontally, a substantial distance, and thus, erratically swerving about, finally land on the bottom, quite by chance in any particular area. This simple experiment demonstrates the importance of the *orientation* of the particle with respect to the path of vertical subsidence. As we have seen, equation (2), the drag force resisting subsidence is a function of the projected area of the particle in the direction of motion. Thus, when a sheet of paper is in a horizontal position, the drag force is great, whereas in contrast, the paper on edge offers a greatly diminished projected area with a consequent increased subsidence velocity. Between these two extremes the rate of subsidence will vary with each slight change in orientation. In spherical particles the rates of subsidence are uniform, but no such uniformity can be assumed for irregularly shaped particles, particularly flocculent material.

Agglomeration. Flocculent particles have a characteristic tendency to coalesce or agglomerate when brought into contact with each other. This increases the size and changes the shape; it also increases the density. The thin, sheetlike flocculent particles expose a large portion of their mass to absorption of water and, hence, lowering of density. Very thin lacy floc particles may thus approach the density of water, with almost complete loss of impelling settling force. In the process of agglomeration, compaction takes place, the framework of the floc is filled in, water is expelled and density increased.

Agglomeration takes place during the process of subsidence. The constantly changing subsidence rate of flocculent material brings about contact between particles, the faster settling overtaking the slower, and, as agglomeration progresses, the rate of settling tends to increase. A moderate degree of turbulence or even artificial stirring may increase the opportunity of contact and enhance agglomeration to such an extent that the time required for sedimentation is reduced.

Opportunity for agglomeration is greater where the concentration of the flocculent particles is high, simply because there exists greater opportunity for contact among the greater number of particles. Consequently, the influence of agglomeration on subsidence is more pronounced in polluted waters of high suspended solids concentration than in those of low concentration. The constantly changing conditions associated with orientation and alteration of size, shape, and density of particles during sedimentation preclude any development of theoretical rates of subsidence which can be relied upon to predict performance of sedimentation of flocculent matter. In practice, periods of 1 or 2 hours are found to be necessary and sufficient.

DISPERSION: SHORT CIRCUITING

Since time of passage is so important a term in hydraulic separation, economy of design and other features call for as uniform a detention time for each and every portion of the flowing liquid as possible. The ideal condition is one in which the flow is strictly *streamline flow* and every small unit volume passes through the tank in the theoretical *detention period,* defined as the time it would take to fill the empty tank at the existing rate of flow. Another measure of tank capacity, the *overflow rate* is defined as the rate of flow in gallons per day per square foot of superficial tank area.

Unfortunately, in practice, the time of passage is neither identical for each portion of water entering a given tank nor even remotely similar in tanks of the same capacity but of different shape, or with different inlet and outlet devices. Some portions of the water may pass through the tank in much less than the theoretical detention time, whereas other portions remain in the tank for much longer periods. The actual detention period, for subsidence purposes, is only the time that a particular portion remains in the tank. The extra removal from those portions which have longer times of passage does not compensate for the poorer results from those with shorter times, so that the net effect is a lower removal than would be expected during the theoretical detention time.

The phenomenon of unequal times of passage for different portions of the same stream entering continuous-flow tanks, commonly referred to as *short circuiting,* is more properly termed *dispersion.* Dispersion is such a dominating influence that it masks the effects of other factors in hydraulic separation. It is futile to attempt to compare the effectiveness of various sedimentation or flotation devices without first determining the relative dispersion in the different units.

THE DISPERSION INDEX. Capen* and Morrill† were among the

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* C. H. Capen, *Eng. News-Record,* **99**, 833, 1927.

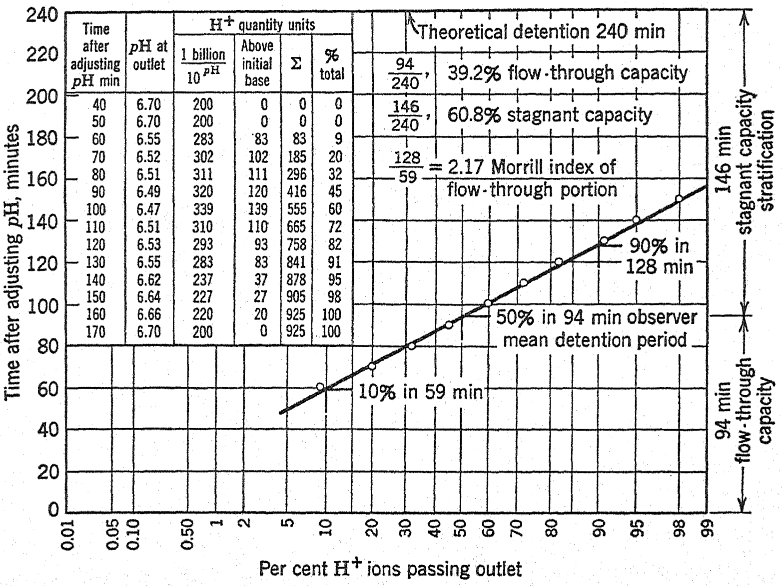
† A. B. Morrill *J. Am. Water Works Assoc.,* **24**, 1442, 1932.

first to evaluate dispersion quantitatively. Morrill defined the *dispersion index* as the ratio of the time required to pass 90 per cent of any incoming portion of the water through the tank to the time required to pass 10 per cent. In ideal stream flow all particles are in the tank for exactly the same period, and the dispersion index is unity. The greater the time spread, the greater the short circuiting or dispersion. The effective capacity of sedimentation tanks and the *actual effective detention time* vary inversely as the dispersion index.

The dispersion index is a powerful tool in evaluating performance of continuous-flow hydraulic units of various designs and is rapidly coming into more general use in studies of water and sewage treatment. It is a measure of the hydraulic characteristics of a unit, reflecting such aspects as dead space, turbulence, channeling, stratification, eddying, and backflow. Perhaps the simplest way to observe these hydraulic characteristics is to introduce a slug of dye into the incoming water and observe its travel through the tank. Invariably it will be noted that a portion of the dye passes through the tank in a much shorter period than the theoretical detention time, whereas a corresponding longer period will be required to clear the tank of the last traces of color. This is a qualitative measure of dispersion characteristics.

DETERMINATION OF THE DISPERSION INDEX. The quantitative determination of the Morrill dispersion index requires measurement, at the outlet of the tank and at equally spaced time intervals, of the concentration of some substance such as salt or acid which had been introduced at the inlet at a certain time and in known quantity. The substance employed should not appreciably affect the density of the fluid. A convenient technique consists in altering the hydrogen ion concentration of the entering water and measuring the *p*H of the effluent. If the quantities of hydrogen ion (concentration times volume of flow over the interval) be summed and plotted (as percentages of the total added or recovered) on a probability scale, against the time of passage, the characteristics of the dispersion will be disclosed. In general it will follow the *normal* distribution of a chance phenomenon (straight line on probability paper), or the distribution may be *skewed*, depending upon the type of inlet and outlet devices.

Figure 79 shows a typical result of the combined effect of *stratification* and *dispersion* in a large deep sedimentation tank as disclosed by a field test based on *p*H adjustment. Although the theoretical detention period was 240 minutes, the observed mean detention was only 94 minutes. Actually, flow was taking place through only 39.2 per cent of the tank; 60.8 per cent of the capacity was totally dead space, principally from stratification in the lower depths. Furthermore, it is noted that *dispersion* took place in the active or flow-through portion; 50 per cent had less than the mean detention of 94 minutes, the first 10 per cent less than 59 minutes, whereas, the last 10 per cent to pass had more than 128 minutes. The Morrill index of the flow-through portion was, therefore, 2.17 (128/59). The mean detention period was not applicable to the total flow, and, therefore, the *effective* detention was actually less than 94 minutes, because of dispersion.



Time after adjusting pH min	pH at outlet	H^+ quantity units			
		$\frac{1\text{ billion}}{10^{pH}}$	Above initial base	Σ	% total
40	6.70	200	0	0	0
50	6.70	200	0	0	0
60	6.55	283	83	83	9
70	6.52	302	102	185	20
80	6.51	311	111	296	32
90	6.49	320	120	416	45
100	6.47	339	139	555	60
110	6.51	310	110	665	72
120	6.53	293	93	758	82
130	6.55	283	83	841	91
140	6.62	237	37	878	95
150	6.64	227	27	905	98
160	6.66	220	20	925	100
170	6.70	200	0	925	100

FIG. 79. Stratification and dispersion based on passage of H+ ions. Sedimentation basin 320′ × 175′ × 15′, theoretical detention 4 hours.

This test illustrates the detrimental effects of stratification in deep tanks, as well as dispersion. Usually in tanks less than 10 feet in depth the entire capacity is subject to flow action, in which case the only influence will be dispersion, and the mean detention determined from dispersion test will approximate the theoretical detention.

Factors Influencing Dispersion. The more important factors which appear to govern dispersion are shape of the tank, location and type of inlet and outlet devices, temperature as affecting stratification, wind action and velocity of flow through the tank. Long narrow tanks with maximum distance between inlet and outlet are favorable to low indices. Shallow rather than deep tanks favor good distribution of flow and minimize stratification. Covered tanks, excluding the sun's rays, assist in preventing stratification and channeling due to differences in temperature at the surface and eliminate wind action. Low velocities, which produce streamline flow, uninterrupted by sudden changes in direction, reduce dispersion. Submerged weirs or multiple inlets and outlets produce lower indices than single port inlet and outlet devices. Guide vanes to distribute the incoming flow across the entire channel are also an aid. However, transverse baffles, intended as obstructions to short circuiting, may actually increase dispersion.

EFFICIENCY OF SEDIMENTATION OF FLOCCULENT MATTER

Schroepfer* has analyzed the performance of more than 30 sewage treatment plants under 150 different operating conditions, relating theoretical detention time to percentage of removal of suspended solids and BOD. He separated these data in accordance with strength of the sewage into groups of 50–100, 100–200, 200–300, and 300–400 parts per million concentration. The two groups of these data, 100–200 and 200–300 parts per million suspended solids, which are of sufficient number to handle statistically, are replotted in Figure 80.

From knowledge of the factors at play in subsidence of flocculent matter, it is logical to expect a decreasing rate of removal with time and an upper limit in efficiency at less than 100 per cent, due to nonsettleable fine solids.

Although this general trend is apparent in Figure 80, there are wide variations in removal of suspended solids for tanks of the same theoretical detention period, and, furthermore, some tanks

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* G. J. Schroepfer, *Sewage Works J.*, 5, no. 2, 209, March 1933.

of small theoretical detention appear to be far more efficient than others two to three times larger. These inconsistencies in actual performance are likewise reflected in rather low-order correlations between theoretical detention and logarithm of suspended solids remaining with coefficients of correlation of —0.55 and —0.48 for sewages of 100–200 and 200–300 parts per million, respectively.

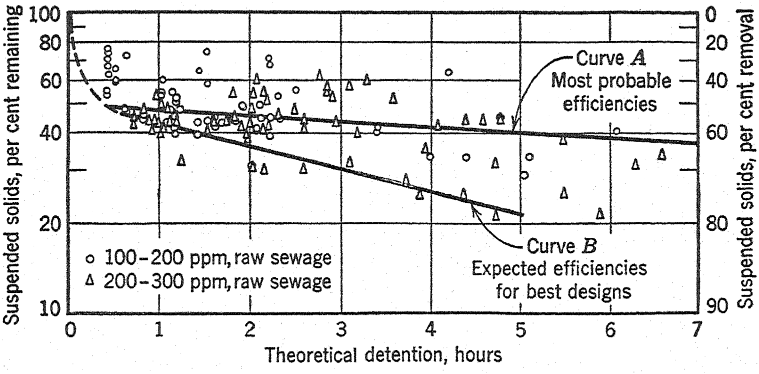

Fig. 80. Efficiency of sedimentation of flocculent matter.

Suspended solids 100 to 200 ppm and 200 to 300 ppm.
Based on operation of 30 sewage treatment works reported by Schroepfer.

There appears to be no significant difference in results, expressed on a percentage basis, between the weak and the strong sewages. Accordingly, curve *A* of Figure 80, the line of best fit through the combined data, may be taken to represent the most probable expected sedimentation efficiencies. Curve *B* is drawn to reflect the expected performance of tanks of the best designs. These comparative efficiencies are shown in Table 46.

Although dispersion indices are lacking for these tanks, from what is known generally of the wide range in index (1.5 to 10.0) in practical installations, it is not surprising that actual performance in the efficiency of hydraulic separation of flocculent suspended solids varies so radically. A more rational basis of design is obviously needed and undoubtedly will be developed along the line of model studies to determine hydraulic characteristics, and more extensive determination of dispersion index of plant scale units correlated to efficiencies.

TABLE 46

EXPECTED PERFORMANCE OF SEDIMENTATION TANKS, BASED UPON OBSERVED EFFICIENCIES

Raw Sewage Suspended Solids 100–300 ppm

Theoretical Detention Period, Hr.	Most Probable Removal of Suspended Solids, Per Cent	Expected Removal of Suspended Solids for Tanks of Best Design
0.5	52	54.0
1.0	53	58.0
1.5	54	61.5
2.0	55	64.5
2.5	56	67.5
3.0	57	70.0
3.5	58	72.5
4.0	59	75.0

FLOTATION

Hydraulic separation by flotation is conveniently dealt with under two categories: *natural flotation* and *induced flotation*. Natural flotation comprises the separation of suspended solids lighter than water, including grease and oil globules, grease- and oil-coated solids and agglomerations of particles entraining gases, which rise and are skimmed from the surface of detention tanks. The laws discussed under sedimentation apply also to flotation. Usually, natural flotation is a process incidental to sedimentation operations, as the quantities of suspended solids in polluted water which respond to this principle are relatively small. However, with wastes high in grease content, the principles of natural flotation may be employed in the separation of grease by a short detention period of 3 to 5 minutes preceding sedimentation operations.

Induced flotation is the principle of hydraulic separation whereby suspended solids gain added buoyancy from air bubbles released or introduced into water. The particles, upon contact with the air bubbles, become attached to them and are thus impelled to rise to the surface where they are held momentarily in the froth of the escaping bubbles. The process is aided by the addition of flotation reagents of two general classes: the frothers, those promoting the formation of froth or foam of density sufficient to retain the suspended particles to permit scraping it from the surface; and the collectors, those which increase the attractive force between the air bubbles and the particles and thus aid induced flotation. These reagents are generally complex heteropolar organic compounds, many of which are selective in their action; that is, effective only in the flotation of specific substances. The selection of a specific reagent is primarily a process of experimentation, as, at present, fundamental information as to the character of these complex compounds and the mode of their action is limited.

The theory of action of flotation reagents is based primarily upon surface phenomena at the liquid, gas and solid interfaces. Frothing is associated principally with wetting agents capable of reducing surface tension around the air bubbles within the water, thus preventing their coalescence when in contact with each other and permitting formation of a froth of considerable stability. The action of collectors is that of a connecting link which attaches the solid particle to the air bubble. The polar portion of the reagent reacts with or is adsorbed upon the surface of the solid particle, while the nonpolar part, which has an affinity for the gas phase, attaches to the air bubble. Collection and buoyancy are thus induced. Collector reagents are effective in the flotation of colloids as well as suspended matter, but do not remove dissolved matter.

The principles of induced flotation have been successfully applied in the treatment of paper mill wastes.* Its value has also been demonstrated in the removal of suspended and colloidal matter from sewage† and of turbidity and color from water.‡

CHEMICAL COAGULATION

DEFINITIONS

Chemical coagulation of nonsettleable solids and colloidal matter involves the interaction of three phases of matter: *dispersed matter,* the *dispersion medium,* and the *collection medium.*

The dispersed matter comprises nonsettleable solids, that is suspended matter of larger size than the true colloids but too small to respond to hydraulic separation by sedimentation. These finely divided suspensoids range in size from the region of 7.0 micron to about 0.2 micron. They constitute a portion of the turbidity in surface waters (clay and eroded soil) and, as organic

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* W. D. Harrison, *Paper Trade J.,* August 17, 1939.

† C. A. Hansen and H. B. Gotaas, *Sewage Works J.,* **15**, 242, 1943.

‡ S. H. Hopper, *J. Am. Water Works Assoc.,* **37**, 302, 1945.

matter, make up about 40 per cent of the total suspended matter of domestic sewage.

The dispersion medium consists of the water itself, with its dissociated H^+ and OH^- ions; all matter in true solution, dissolved molecules and their dissociated ions; and the colloidal sols. For our present needs the colloids may be taken to include all material of less than 0.2 micron in diameter, capable of passing a Seitz filter, but not in true solution.* In surface waters they make up the organic color and the finer turbidity. In sewages they are organic in nature and comprise 10 per cent or more of the total BOD content, varying according to the somewhat arbitrary size limitations and methods of measurements adopted by various investigators.

The collection medium may be represented by coagulated dispersed matter, coagulated colloids (colloidal gels), coagulated chemical precipitates, or any combination of these. Coagulation, taken broadly, involves both collection of dispersed matter and agglomeration into suspended particles of sufficient size to induce subsequent sedimentation. According to the type of collection medium employed, we may deal with *self-coagulation,* where the materials to be removed serve as their own collecting medium, or *induced coagulation,* involving the introduction of a collecting medium, the *coagulant* upon which the dispersed matter deposits. Nonsettleable dispersed matter can be removed to a limited extent by self-coagulation simply by stirring, which brings about contact of the dispersed matter and its agglomeration. Removal may be further enhanced by altering the dispersion medium, as by changing the reaction, *p*H. Most colloidal sols are dependent upon induced coagulation for their separation, although certain organic colors can be removed by self-coagulation under proper alteration of the dispersion medium. Organic matter in true solution is not removed by coagulation of either type.

The end result of chemical coagulation, manifesting itself as the combined action of dispersed matter, the dispersion medium, and the collection medium, can be modified by independent alteration of these three factors. The mode of action of such changes or, at least, observation of the end effects, is essential to an understanding

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* This classification is suggested by Gehm in his outstanding work on coagulation of sewage conducted at the N. J. Agr. Exp. Sta., Dept. Water and Sewage Research. H. W. Gehm, *Sewage Works J.*, **11**, 738, 1939.

of the complex phenomena and an explanation of the wide differences in operating results of the treatment of polluted waters by chemical coagulation.

INFLUENCE OF DISPERSED MATTER

It is commonly supposed that a small quantity of turbidity aids chemical coagulation. However, alteration of the concentration of dispersed matter, under controlled conditions, fails to substantiate this supposition. Gehm,* experimenting with chemical coagulation of sewages, found that increasing or decreasing the *settleable solids* concentration does not affect clarification nor alter coagulant requirements. The same is true of the *nonsettleable solids* of various sizes (larger than colloids). Similarly, in water treatment no appreciable change in clarification and in coagulant requirements is associated with alterations in the concentration of suspended matter by the addition of artificial turbidity or the return of large quantities of previously settled floc. It can be concluded that dispersed particles larger than 0.2 micron have little if any effect on the coagulant requirements for the chemical coagulation of water and sewage. The major factors which influence the quantity of coagulant to effect chemical coagulation of the dispersed matter and the colloids must, therefore, be found in the dispersion medium, the collection medium or both.

INFLUENCE OF THE DISPERSION MEDIUM

The characteristics of the dispersion medium include all the physical and chemical properties of the water; *p*H, temperature, cation and anion concentrations, dissolved matter, and colloids. All these have been demonstrated by various workers to influence chemical coagulation. Not only does each factor influence the end results, but also they are so interrelated that the importance of individual influences depends upon the particular combination of factors involved. Further to complicate evaluation, these influences of the dispersion medium are, in turn, affected by the collection medium, that is, by the type and quantity of coagulant employed. Consequently, no generalizations of coagulation conditions and

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* Harry W. Gehm, *Sewage Works J.*, **8**, no. 3, May 1936; **13**, no. 4, July 1941; **10**, no. 6, November 1938.

TABLE 47

SYNTHETIC WATERS

Number	Character of Dispersion Medium	Coagulant	Time for Floc Formation, Min	*p*H Range	Remarks
1	Distilled water Sodium hydroxide	Alum	4	7.4	Rather sharp optimum *p*H.
			10	6.8 to 7.7	
			20	6.7 to 7.7	
2	Distilled water Sodium bicarbonate	Alum	3.5	7.3 to 7.7+	Wider range in optimum *p*H where sodium bicarbonate replaces sodium hydroxide.
			10	6.7 to 7.7+	
			20	6.6 to 7.7+	
3	Distilled water Sodium hydroxide Sodium sulphate (125 ppm)	Alum	3.5	6.3	Sulphate ion widens *p*H range on the acid side.
			4	5.0 to 7.2	
			10	4.4 to 7.7	
			20	4.2 to 7.8	
4	Distilled water Sodium hydroxide Sodium chloride (250 ppm)	Alum	4	7.2	Chloride ion widens *p*H range slightly.
			10	6.0 to 7.8	
			20	5.8 to 7.8	
5	Distilled water Sodium hydroxide	Ferric sulphate	4	6.2	Floc failed to form beyond *p*H 4.8 and 7.2.
			10	5.8 to 6.8	
			20	5.5 to 6.9	
6	Distilled water Sodium bicarbonate	Ferric sulphate	3	6.2	Floc failed to form beyond *p*H 4.5 and 7.2.
			10	5.2 to 6.8	
			20	5.0 to 7.0	
7	Distilled water Sodium hydroxide Sodium sulphate (25 ppm)	Ferric sulphate	3	6.4	Floc formed at two *p*H zones, acid side below *p*H 6.8 and alkaline side above *p*H 8.5, with poor or no formation between *p*H 7.0 and 8.5.
			5	4.8 to 6.4	
			10	4.8— to 6.8 and at 9.1	
			20	4.8— to 6.8 and at 8.4	

8	Distilled water	Ferric sulphate	3	6.4	Floc formed at two *p*H zones, on acid and alkaline side, with weak formation between *p*H 7.0 and 8.5.
	Sodium hydroxide		5	3.8 to 6.6 and at 9.4	
	Sodium sulphate (250 ppm)		10	3.8 – to 6.8 and 8.0 to 9.4	
9	Distilled water	Ferric sulphate	3	6.4	Floc formed at two *p*H zones, acid side below *p*H 6.8 and alkaline side above *p*H 8.5, with poor or no formation between *p*H 7.0 and 8.5
	Sodium hydroxide		5	5.4 to 6.8	
	Sodium chloride (25 ppm)		10	5.1 to 6.9 and 8.9 to 9.4+	
10	Distilled water	Ferric sulphate	3	6.4	Increase in chloride aided formation in the range *p*H 7.0 to 8.5.
	Sodium hydroxide		5	5.0 to 6.8 and 8.0 to 9.4+	
	Sodium chloride (250 ppm)		10	4.3 to 9.4+	
			20	4.0 to 9.4+	
11		Chlorinated copperas			Chlorinated copperas, about the same as ferric sulphate, nos. 7, 8, 9 and 10.
12	Distilled water	Ferric sulphate	2	8.0	Calcium cation more effective on alkaline side than sodium.
	Sodium hydroxide		3	6.0 to 9.4+	
	Calcium chloride (25 ppm)		10	5.0 to 9.4+	
13	Distilled water Sodium hydroxide	Ferric sulphate		7.0 to 9.6	Floc failed to form.
14	Distilled water	Ferric sulphate	4	9.6	Calcium cation a distinct aid on the alkaline side.
	Calcium hydroxide		5	8.8	
			10	7.6	
			15	7.3	

TABLE 47 (*Contd.*)

Number	Character of Dispersion Medium	Coagulant	Time for Floc Formation, Min	*p*H Range	Remarks
15*	Distilled water	Alum			
	Calcium carbonate	10 ppm			
	Alkalinity (20 ppm)		40	7.2	Optimum alkalinity
	Alkalinity (20 ppm)		60	6.8 to 7.4	50 to 75 ppm.
	Alkalinity (40 ppm)		16	7.2	
	Alkalinity (40 ppm)		20	7.0 to 7.3	
	Alkalinity (40 ppm)		40	6.75 to 7.45	
	Alkalinity (75 ppm)		10	7.1	
	Alkalinity (75 ppm)		20	6.7 to 7.45	
	Alkalinity (75 ppm)		40	6.4 to 7.5	
16*	Distilled water Alkalinity 25 ppm Calcium sulphate (100 ppm)	Alum 10 ppm			Calcium sulphate widened optimum *p*H on acid side about the same as that produced by increase in alkalinity. See no. 15.
17*	Distilled water Alkalinity (50 ppm) Sodium chloride	Alum 10 ppm			Sodium chloride up to 1000 ppm produced no effect on time of floc formation.
18*	Distilled water	Alum			Optimum alum dose approximately 20 ppm for rapid floc formation.
	Alkalinity (20 ppm)	15 ppm	25	6.6 to 6.8	
		20 ppm	14		
		30 ppm	9		

		Influence of Silica Sol			
	Distilled water	Alum			
19*	Alkalinity 20 ppm	3 ppm	40		Good but not excellent floc.
	Silicates as SiO_2(4 ppm)	4 ppm	5.5	6.4	Silicates produced rapid formation with greatly reduced alum dose and floc formed as "immense" agglomerations.
		5 ppm	4.7		
		10 ppm	4.5		
		Influence of Temperature			
	Distilled water	Ferric sulphate			At threshold doses of coagulant the optimum *p*H is shifted toward the alkaline side with drop in temperature. At high coagulant doses the effect of temperature is not apparent.
20*	Sodium hydroxide				
	Temperature, °C 3.6	2.0 ppm (as Fe)	26	7.35	
	15.3	2.0 ppm (as Fe)	21	7.25	
	28.3	2.0 ppm (as Fe)	23	7.00	
	3.6	3.15 ppm (as Fe)	17	7.15	
	15.3	3.15 ppm (as Fe)	14	7.05	
	28.3	3.15 ppm (as Fe)	15	7.05	
	3.6	4.3 ppm (as Fe)	11	7.0	
	15.3	4.3 ppm (as Fe)	10	7.1	
	28.3	4.3 ppm (as Fe)	10	7.0	

No.'s	*Authorities*
1– 4	A. P. Black, O. Rice, and E. Bartow, *Ind. Eng. Chem.*, 25, 811, 1933.
5–14	E. Bartow, A. P. Black, and W. E. Sansbury, *Ind. Eng. Chem.*, 25, 898, 1933.
15–19	J. R. Baylis, *J. Am. Water Works Assoc.*, 29, 1355, 1937 *Water Works & Sewerage*, 84, 426, 1937.
20	T. R. Camp, D. A. Root, and B. V. Bhoota, *J. Am. Water Works Assoc.*, 32, 1913, 1940.
*	Authors specified time for formation of *good* floc.
*	Baylis specified time for *excellent* floc formation.

TABLE 48

NATURAL WATERS

Number	Character of Dispersion	Coagulant	Time for Floc Formation, Min	pH Range	Remarks
1	Lake Michigan water Alkalinity 120 Ca 35 ppm Mg 10 ppm SO_4 12 ppm Cl 5 ppm CO_2 and lime used to vary pH	Alum 7.5 ppm	11 15 20 40	6.7 6.0 to 7.2 5.75 to 7.4 5.5 to 7.5	Natural waters much wider range in optimum pH than shown by synthetic waters.
2	Rain water collected from roof gutters. Calcium carbonate 40 ppm Silicate 0.4 to 1.2 ppm	Alum 10 ppm	25 30 40	7.1 6.4 to 7.4 6.2 to 7.5	Much wider range in optimum pH than shown by synthetic waters.
			Influence of Neutral Salts		
3	Lake Michigan Water and other natural waters plus neutral salts	Alum			Addition of neutral salts (sulphates and chlorides) had little or no effect upon coagulation of natural waters.
4	Hackensack River water plus cations and anions	Alum or chlorinated copperas			Addition of calcium $(^{++})$, sulphates $(^{--})$ and chlorides $(^{-})$ had no apparent effect on coagulation of natural waters.

			Influence of Temperature and pH		
5	Hackensack River water				
	Color 38 ppm	Alum		5.4	Color reduced to 8 ppm.
	Mixed 1 hour; settled 1 hour	26 ppm		5.0 to 6.0	Color reduced below 15 ppm.
	Temperature 24°C			Above 6.2	Poor color removal and poor floc.
6	Hackensack River water	Alum		5.3	Color reduced to 2 ppm.
	Color 48 ppm	34 ppm		4.0 to 5.8	Color reduced below 15 ppm.
	Mixed 1 hour; settled 1 hour			Above 6.2	Poor color removal and poor floc.
	Temperature 24°C				
7	Hackensack River water Color 38 ppm Mixed 1 hour; settled 1 hour	Alum			Reducing temperature increased the *p*H range in which good removal of color took place.
	Temperature, °C 24	26 ppm		6.7	Color reduced to 30 ppm.
	16	26 ppm		6.7	Color reduced to 16 ppm.
	10	26 ppm		6.7	Color reduced to 10 ppm.
8	Hackensack River water	Chlorinated copperas			Temperature influence similar to no. 7.
9	Hackensack River water	Chlorinated copperas		3.8 to 4.8	Color removal good and rapid floc formation.
	Color 50 ppm			8.0 to 10	Color rem. poor and poor agglomeration of floc.
	Mixed 1 hour; settled 1 hour	34 ppm		4.8 to 8.0	Color imparted and poor floc formation.
	Temperature 24–20° C				
			Influence of Silica Sol		
10	Lake Michigan water	Alum			Very rapid and excellent coagulation took place at both acid and alkaline *p*H zones, and slower formation of floc between *p*H 7.6 and 8.8. Floc formed into "immense" granular agglomerations.
	Silica sol as SiO_2 3 ppm	10 ppm	7	6.5	
			2	10.3	
			10	5.5 to 7.5	
			10	8.7 to 10.3+	
			15	5.5 to 10.3+	

TABLE 48 (*Contd.*)

Number	Character of Dispersion	Coagulant	Time for Floc Formation, Min	*p*H Range	Remarks
11	Several surface waters, New York State Silica, 4 to 8 ppm neutralized, aged	Alum			Marked improvement of floc formation larger size and toughened. (Sodium silicate added without neutralization of excess alkalinity definitely inhibited coagulation.)

No.'s	*Authority*
1– 3, 10	J. R. Baylis, *loc. cit.*
4– 9	C. J. Velz, *Civil Eng.*, 4, 345, 1934.
11	T. M. Riddick, *J. Am. Water Works Assoc.*, 33, 908, 1941.

results have been attempted. Tabulation and discussion of the influences of some of the more important conditions, as observed by various workers, will serve to indicate the complexity of the subject and contribute to a better understanding of its nature.

Tables 47, 48, and 49 illustrate typical observations upon chemical coagulation of synthetic waters, natural waters, and sewages, respectively.

Hydrogen Ion Concentration. The reaction of the dispersing medium, as expressed by its *p*H, has long been observed to be an important factor in coagulation. There appears to be an optimum *p*H zone for maximum coagulation and agglomeration, with a minimum of coagulant. This varies with different coagulants and with their concentrations and, in turn, is shifted along the scale or the zone is widened or narrowed by concentration of certain anions, cations, colloidal sols, and by temperature. Optimum *p*H, therefore, is not a fixed stable value. It varies with the other characteristics of the dispersion medium.

Anions of certain salts modify coagulation results in combination with hydrogen (H^+) and hydroxyl (OH^-) ions. The sulphate ion (SO_4^{--}) in synthetic waters tends to widen the optimum *p*H zone for coagulation, principally on the acid side, and the chloride ion (Cl^-) improves coagulation and extends the optimum *p*H zone but somewhat more than sulphate on the alkaline side. The carbonate (CO_3^{--}) and bicarbonate (HCO_3^-) ions also improve coagulation in synthetic waters. These influences of anions are pronounced in synthetic waters, but not detectable in the coagulation of most natural waters, where other factors overshadow them.

Cations, principally bivalent calcium (Ca^{++}), play an important role in combination with high concentration of hydroxyl ions, or with an iron coagulant. Gehm has demonstrated that calcium ions in combination with hydroxyl ions can promote marked self-coagulation of dispersed matter in sewages (Table 49, no. 4). He also demonstrated that the calcium ion with ferric coagulant acts as a catalyst, greatly aiding induced coagulation and clarification (Table 49, no. 5). Calcium alone has no effect, nor is the hydroxyl alone effective. Monovalent cations such as sodium (Na^+) do not influence coagulation.

Collodidal Sols determine, to some extent, the removal of dispersed and colloidal matter by chemical coagulation. Other constituents of the medium being constant, the quantity of coagulant

TABLE 49

Municipal Sewages and Industrial Wastes

Number	Character of Dispersion Medium	Coagulant	*p*H	Evaluation of results Removal of Turbidity Per Cent	Remarks
1	Municipal sewages. *p*H adjusted with sulphuric acid, lime and sodium hydroxide. Mixed 20 min. settled 1 hr.	Ferric chloride Fe (ppm) 0	Optimum range: 2.7 to 3.2 and 10.0 to 11.0	80	Two optimum *p*H zones with poor coagulation between *p*H 4.0 and 9.0.
		5	3.1 to 3.5 and 10.5 to 11.0	90	
		15	2.3 to 4.6 and 8.7 to 11.0	90	
2	Like no. 1	Ferric chloride, ferric sulphate, chlorinated copperas	Two optimum zones as above		Similar to no. 1. Ferric chloride slightly superior to other salts.
Influence of Acids on Self-Coagulation					
			Adjusted to:	Turbidity remaining, ppm	
3	Like no. 1. *p*H adjusted with: Hydrochloric acid	No coagulant	2.5	80	Both acids induce self-coagulation. Hydrochloric acid superior to sulphuric. Maximum coagulation at *p*H 3.0 to 3.2.
			3.0	30	
			3.2	28	
			4.0	55	
			5.0	110	

	Sulphuric acid	No coagulant	2.5	80	
			3.0	45	
			4.0	100	
			5.0	130	
			Influence of Calcium and Hydroxyl Ions		
4	Like no. 1. *p*H adjusted with: Lime ($Ca(OH)_2$)	No coagulant	7.0	155	Lime induced self-coagulation. The $(OH)^-$ ion is not effective without the Ca^{++} ion which, however, does not combine with the floc but remains in the supernatant.
			8.0	138	
			9.0	105	
			10.0	55	
			10.5	40	
	Sodium hydroxide (NaOH)	No coagulant	7.0	155	
			8.0	155	
			9.0	155	
			9.5	150	
			10.0	158	
			10.5	158	
5	Like no. 1, without *p*H adjustment. Calcium chloride added $CaCl_2$, ppm	Ferric chloride 10 ppm			Calcium ion (Ca^{++}) is an aid to coagulation with ferric chloride without *p*H adjustment. Sodium chloride in place of calcium chloride failed to show a similar effect. Calcium chloride without ferric coagulant failed to bring about coagulation or clarification.
	0			95	
	20			70	
	40			42	
	60			30	
	80			25	
	100			22	

TABLE 49 (*Contd.*)

Number	Character of Dispersion Medium	Coagulant	*p*H	Evaluation of results Removal of Turbidity, Per Cent			Remarks
	Influence of Silica Gel						
				Removal percent, of: Turbidity	Suspended solids	BOD	
6	Waukegan, Ill., municipal sewage	Alum, ppm					
	Sodium silicate added, ppm						
	0	23		42	73	58	Poor floc, fine
	6.6	17		62	84	76	Very large floc
7	Chicago, Ill., west side						
	With Sodium silicate added	Ferric chloride				73	Sodium silicate improved coagulation with alum or with ferric chloride only slightly. It improved the values of copperas and of chlorinated copperas materially bringing the latter to above that of ferric chloride or alum alone. Lime brought about the same improvement in coagulation with chlorinated copperas as did sodium silicate. These laboratory results were confirmed by experimental plant operation.
		Alum				70	
		Copperas				75	
		Chlorinated copperas				66	
	Without sodium silicate	Ferric chloride				69	
		Alum				68	
		Copperas				60	
		Chlorinated Copperas				57	
	With lime only	Chlorinated copperas				66	
8	Sewage, Grand Forks, N. D.	Alum 35 ppm					
	Silica, ppm 0			77	58	30	On the acid side silica widened the optimum *p*H range to as low as 4.9. It was less effective on the alkaline side.
	10			92	96	50	

Influence of Protein Sols

	Municipal sewages	Ferric chloride		Turbidity remaining, ppm	The optimum concentration of protein (5 ppm) produced large floc which formed and settled rapidly. At 40 ppm protein was detrimental. Results with alum similar. With 6 municipal sewages the average reduction in coagulant requirements, when supplemented with protein, was 25 per cent.
	No protein	10 ppm		155	
	Gelatin			50	
	Gluten			55	
	Zein			62	
	Peptone			90	
	Casein			95	
10	Municipal sewages Gelatin, 5 ppm. *p*H adjusted with lime and sulphuric acid	Ferric chloride	Above 8.5		Fine floc, slow settling.
			Below 8.5		Large ball-like floc, rapid settling.
			3.0 to 6.0		Optimum *p*H range for turbidity removal.
11	Municipal sewages Gelatin 5 ppm. *p*H adjusted to optimum	Ferric chloride ppm (Fe)			Coagulant and *p*H adjusted for complete clarification with gelatin as coagulant aid.
		20	7.5		
		17	7.0		
		15	6.0		
		12	5.5		

Number	Authority
1	W. Rudolfs and H. W. Gehm, *Sewage Works J.*, 8, 195, 1936.
2–5	H. W. Gehm, *Ibid.*, 13, 239, 1941.
6	H. G. Swope, *Ibid.*, 11, 93, 1939.
7	E. Hurwitz and M. Williamson, *Ibid.*, 12, 562, 1940.
8	C. W. Christenson and I. Levine, *Trans. SACE*, 36, 71, 1940.
9–11	H. W. Gehm, *Sewage Works J.*, 13, 1110, 1941.

required is dependent upon the proportion of colloidal sols. The coagulant demand appears to be associated with the organic rather than the inorganic fraction of the colloids.* The classification of colloidal sols and quantitative relationships between colloids and coagulant dosage have not been developed, primarily because of the difficulties in isolating the colloidal from the dissolved fraction.

Natural surface waters relatively free of pollution except colloidal organic colors offer a quantitative measure of colloids, as color concentration, and an opportunity to evaluate their relation to coagulant demand. Figure 81 shows the relation between alum dosage and color concentration in raw water of reasonably constant conditions of dispersion medium and identical end results of coagulation treatment. This curve is typical of impounded waters. It is apparent that there is a definite relationship between colloids and coagulant requirement, the dosage varying interlinearly with the log of the colloid concentration. That is, doubling the colloid concentration, at any level, requires the addition of a constant quantity ($0.3m$) of coagulant for equivalent results. The slope and position of the line (the constants m and b) depend on the dispersion medium and type of coagulant.

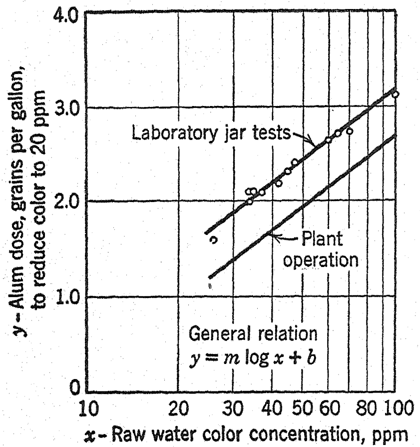

Fig. 81. Typical relation between coagulant requirements and colloidal color concentration.

Dispersion medium, natural waters; temperature, 24° C; pH, 6.7 to 7.2.

Although it is known that the colloidal fraction determines coagulant demand, quantitative correlation for general practical use awaits the accumulation of sufficient basic data. For the present, therefore, coagulant dosage must be determined by cut-and-try procedure with laboratory jar tests (Figure 82).

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* H. W. Gehm, *Sewage Works J.*, **11**, 738, 1939.

Silica Sols. Thus far we have dealt with colloidal sols in polluted water which promote dispersions and prevent coagulation by exercising a coagulant demand. There are certain colloidal sols which greatly aid coagulation and agglomeration.

Baylis in his pioneering work has shown that colloidal silicates are a distinct aid to coagulation and greatly hasten and improve the agglomeration of floc into unusually large granular particles of high subsidence velocity; also that small quantities of silicates present in natural waters greatly widen the pH zone for good coagulation.

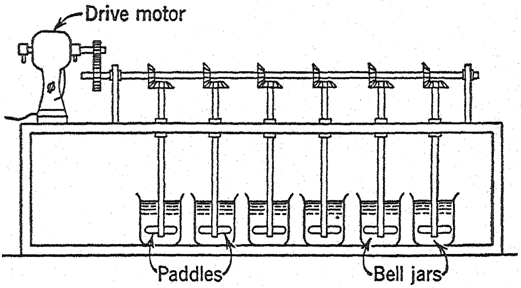

Fig. 82. Bench mixing apparatus for coagulation control.

This helps explain the divergence in results with synthetic waters prepared without added silicates (Table 47). Variations in natural silica content doubtless tends to explain the widely varying results obtained by similar treatment of otherwise similar natural waters.

To be effective, silica must be present as a colloidal sol; hence, special preparations are required. Sodium silicate (in ratio 1 Na_2O to 3.2 SiO_2) is caused to react with acid or acid-forming materials to release the silica. The mixture is held through an aging period during which miscelle growth occurs. When the miscelles have reached the desired size, further growth is halted by dilution. A reasonably stable silica sol results. Excessive growth of miscelles will cause their interlocking and a change of the colloidal sol into a gel. Gelation may occur with time owing to instability of the prepared solutions. Commercial preparations are available which are highly stable.* The silica sol bears a negative charge and is highly contractive.

* H. R. Hay, *J. Am. Water Works Assoc.*, **36**, 626, 1944.

When used with alum, the minimum quantity of silica (as SiO_2) to produce nearly maximum coagulant aid is approximately 40 per cent of the quantity of alum. Excessive dosage is detrimental and increases coagulant demand. Silica is effective also with iron coagulants, particularly copperas, but in some instances it has been of little aid with ferric chloride.

Silica is proving an economical aid in treatment of water and sewage and is particularly valuable in increasing the efficiency of hydraulic separation by sedimentation following coagulation treatment (Tables 48 and 49).

PROTEIN SOLS of several kinds, added in small quantities with iron or alum, improve the coagulation of sewage. Colloidal gelatin, gluten, zein, peptone, and casein assist in agglomerating the floc into large ball-like particles of extremely high subsidence velocity. This is particularly pronounced when the *p*H is on the acid side. A 25 per cent reduction in coagulant is possible with a protein dosage of 5 to 10 parts per million (Table 49).

INFLUENCE OF TEMPERATURE. The viscosity of water increases with lowered temperature, and sedimentation is slowed down in the more viscous medium. At winter temperatures poor sedimentation has been offset by greater coagulant doses, and this has led to the general belief, based upon practical experience, that coagulation is adversely affected by lowered temperature.

Lower temperatures, however, appear to favor some of the coagulation reactions (Table 48, no. 7) and to shift the optimum *p*H zone toward the alkaline side (Table 48, no. 20). These influences are more manifest when minimum threshold doses are being applied and can be offset by *p*H adjustment.

THE COLLECTION MEDIUM

Collection media are of two general types: agglomerated dispersed or colloidal matter, resulting from self-coagulation; and agglomerated chemical precipitates (floc) formed by induced coagulation resulting from the addition of a coagulant.

SELF-COAGULATION. The collection media of self-coagulation can be formed by mechanical agitation of dispersed matter or by air diffusion. Increased clarification of polluted waters, high in suspended solids, can thus be effected without the aid of adjustments in the dispersion medium or the use of coagulants. Efficiency is limited to dispersed suspended solids removal, with less effect on BOD removal, as the colloidal fraction is unaffected. Adjusting the pH of the dispersion medium to the vicinity of 3 with agitation, greatly increases the self-coagulation of nonsettleable dispersed matter. Similarly, adding lime, with agitation, progressively increases removal of dispersed matter with increase in pH. The hydroxyl ion alone, however, without the calcium ion, does not suffice. Calcium and hydroxyl ions together act as catalysts to self-coagulation (Table 49, no. 4).

Induced Coagulation requires the addition of a coagulant capable of forming an insoluble collection medium. The trivalent metallic salts of aluminum and iron are most widely employed in the treatment of water and sewage. In addition to the constituents of the dispersion medium already discussed, sufficient alkalinity must be present to react with the coagulant to form the insoluble precipitate. According to Baylis,* this precipitate is a hydrous oxide of the metal, forming first as particles of colloidal size, then collecting into minute flexible irregular filaments or chains which interlace into a loose formation of gelatinous particles, spongelike in structure and flocculent. The porous lacy character of the structure produces an enormous increase in volume in comparison with the volume of coagulant used, providing a maximum area for surface contact. Finally, the lacy flocculent formations agglomerate into particles of greater size and density, capable of responding to hydraulic separation by subsidence. This material, formed in the dispersion medium by the reaction of alkalinity with the coagulant, constitutes the collection medium for induced chemical coagulation.

REACTIONS. The chemical reactions involved are as follows:

ALUM; FERRIC SULPHATE

$$Al_2(SO_4)_3 + 3Ca(HCO_3)_2 = 3CaSO_4 + 2\mathit{Al(OH)_3} + 6CO_2$$
$$Fe_2(SO_4)_3 + 3Ca(HCO_3)_2 = 3CaSO_4 + 2\mathit{Fe(OH)_3} + 6CO_2$$

CHLORINATED COPPERAS

$$6FeSO_4 + 3Cl_2 = 2FeCl_3 + 2Fe_2(SO_4)_3$$
$$2FeCl_3 + 3Ca(HCO_3)_2 = 3CaCl_2 + 2\mathit{Fe(OH)_3} + 6CO_2$$
$$Fe_2(SO_4)_3 + 3Ca(HCO_3)_2 = 3CaSO_4 + 2\mathit{Fe(OH)_3} + 6CO_2$$

FERRIC CHLORIDE AND SULPHATE

As above

Italicized compounds in each instance form the floc.

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* J. R. Baylis, *Water Works & Sewerage*, *77*, 147, 1930.

Agitation is necessary to bring the collection medium into intimate contact with the dispersed matter and the colloids and thus facilitate their collection in or on the floc surface. Diffused air or mechanical stirring may be employed. Agitation should insure uniform distribution of the collection medium without deposit of floc and without breaking up agglomerations. Agglomeration may be developed gradually during the process of agitation or separately following agitation by upward flow through an accumulation of previously agglomerated floc, which produces almost instantaneous agglomeration.

The time required for formation of the collection medium and its contact with dispersed and colloidal material to be collected depends upon the quantity of collection medium employed and the deviation from optimum conditions of the dispersion medium. Excess dosage of coagulant and *p*H adjustment of the dispersion medium to optimum shorten the contact time to approximately 15 minutes in the laboratory test jar. Under average working conditions, in a continuous-flow tank having a dispersion index of two or less, 30 minutes contact is generally a minimum.

Uniform agitation of all portions of the liquid is essential; hence the importance of a low dispersion index. If more than 15 per cent of the water passes on to the sedimentation tanks before it has received the minimum contact time for floc formation and agglomeration, substantial quantities of nonsettleable floc will remain in the effluent of the sedimentation units. The key to good hydraulic separation following chemical coagulation is good agglomeration prior to sedimentation. The recently discovered silica sols and protein sols referred to previously are noteworthy as aids to agglomeration and, hence, final clarification.

THEORY OF COAGULATION

The complexities of coagulation will doubtless be explained, eventually, upon the basis of colloidal and physical chemistry. Ostwald,* in summarizing progress, sets forth a number of theories in approximately the historical sequence of their development:

Neutralization of charge and equivalent ion exchange.
Critical chemical potential.

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* W. Ostwald, *J. Phys. Chem.*, **42**, 981, 1938. The Williams & Wilkins Co.

Adsorption.
Electrokinetic potential.
Density of charge instead of magnitude of charge.
Compression of double layer.

Although each theory explains certain modes of action, none affords a complete quantitative basis of predicting coagulation results for practical application in the design and operation of treatment works.

In discussing these theories Ostwald points out:

> A sol is composed not only of a dispersed part but also of its dispersion medium. So far the properties of the dispersed part, i.e., of the miscelles, have always stood in the foreground of the theory. Their composition, magnitude of charge, their potential, their double layer and its changes, etc., were the center of theories advanced. The role of the dispersion medium was of decidedly less importance. The dispersion medium was considered in the theory primarily as the carrier of the miscelles and of the stabilizing and coagulating ions.

He presents a new theory, placing the *dispersion medium,* rather than the dispersed miscelles, in the foreground. The inner structure of an electrolyte solution comprises an ionic lattice held together by interionic attraction. A measure of this attraction, and therefore of the inner stability of the lattice, is termed the *coefficient of activity*. Ostwald considers the colloidal miscelles to be built into and subject to the stability of this ionic lattice.

> The comparatively giant miscelles are built into the highly disperse ionic lattice. If we have a stable sol, the interionic force will carry these miscelles. If the sol is coagulated by dialysis, the interionic forces become too weak to carry the particle any longer. The mutual lattice is torn apart. If the sol coagulates by an increase in electrolyte concentration, a kind of "auto-cleansing" of the statistical ionic lattice takes place. The interionic forces become so large that they drive the miscelles together and expel them. It is not the miscelles which coagulate owing to mutual attraction; the dispersion medium coagulates the miscelles by aggregation and expulsion from the ionic lattice.

Ostwald's theory, therefore, hinges upon the *coefficient of activity* of the dispersion medium as the determining variable of coagulation. Since the coefficient of activity can be determined, Ostwald's approach offers a hope of a quantitative evaluation of the complex phenomenon of coagulation.

CHEMICAL AND PHYSICAL PRINCIPLES

There are several principles employed in the treatment of waters which, unlike coagulation, are based upon rather direct, simple, and well-understood chemical and physical reactions. These may conveniently be grouped and discussed together. The group includes *aeration, precipitation, ion exchange,* and *adsorption.*

AERATION

THEORY. Aeration involves an exchange of gases between the liquid and the gas phases, either the addition of oxygen to the water or the removal of carbon dioxide (CO_2), hydrogen sulphide (H_2S), or volatile compounds associated with taste or odor.

Gas exchange involves two basic phenomena, *absorption* and *diffusion.* A water surface, exposed to an overlying gas, will absorb that gas up to the point of saturation where equilibrium becomes established and there is no further transfer. The rate of absorption is proportional to the saturation deficit (see p. 403).

Diffusion transfers the dissolved gases internally. The rate of diffusion is proportional to the concentration gradient in the direction of diffusion or to the difference in concentration between two points unit distance apart. If the water is supersaturated with any gas, that gas tends to escape from the water by the reverse processes of outward diffusion and removal at the surface.

Saturation of a gas in water is a function of the partial pressure of that gas in the overlying atmosphere (p. 290). Thus, for a solution of any gas in water, exposed to an atmosphere free of that gas, the saturation value is zero, and aeration will remove the gas completely.

In removal, as in absorption, the rate of transfer is proportional to the difference between the existing and the saturation concentrations. The farther above or below saturation, the faster *the rate* of transfer. These relations are illustrated in Figure 83. The actual concentration at saturation is dependent upon specific solubility, temperature and the partial pressure of the gas in the atmosphere.

APPLICATION. The process of gas transfer through natural aeration is much too slow for practical application in water treatment. Aeration, as used in treatment, implies a process whereby natural aeration is greatly accelerated. Three methods are commonly employed: *mixing, spraying,* and *air diffusion.* Mixing accelerates the transfer of gases by bringing water from lower depths to the surface and, in turn, removing surface layers to lower depths, thus aiding transfer by shortening the distances through which diffusion must operate. Spraying the water in fine droplets through the air or diffusing small bubbles of air through the water increases the area of exposure between the gas phase and the water phase and thus accelerates transfer. Spraying and air diffusing are both more efficient than simple mixing.

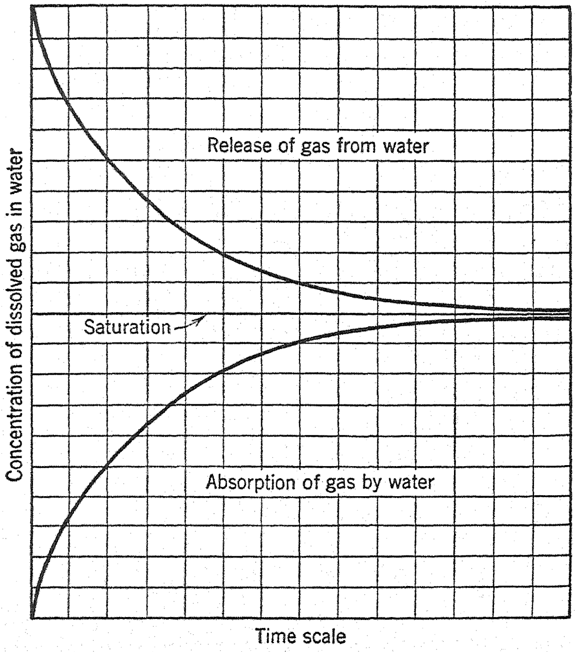

FIG. 83. The relative rates of gas exchange during aeration of water.

PRECIPITATION

Precipitation, as distinguished from coagulation, involves the removal of an undesirable constituent from solution by causing it to react chemically with an added reagent to form an insoluble compound. It is employed in water softening, in *p*H adjustment (p. 466), and in the removal of iron and manganese by aeration.

The type and quantities of chemical reagents required for any specific purpose are determined from the basic reaction equations although the reactions do not always go to completion, and the actual chemical dosage may vary somewhat from that computed.

TYPICAL REACTIONS. The following basic reactions are typical:

NEUTRALIZATION OF CARBONIC ACID, *p*H ADJUSTMENT

(1) $CO_2 + H_2O = H_2CO_3$
(2) Lime $CaO + \mathit{H_2CO_3} = \mathbf{CaCO_3} + H_2O$
(3) Hydrated lime $Ca(OH)_2 + \mathit{H_2CO_3} = \mathbf{CaCO_3} + 2H_2O$
(4)* Sodium hydroxide $2NaOH + \mathit{H_2CO_3} = Na_2CO_3 + 2H_2O$

PRECIPITATION INVOLVING BICARBONATES

(5) Hydrated lime $Ca(OH)_2 + \mathit{Ca(HCO_3)_2} = \mathbf{2CaCO_3} + 2H_2O$
(6) Hydrated lime $2Ca(OH)_2 + \mathit{Mg(HCO_3)_2} = \mathbf{Mg(OH)_2} + \mathbf{2CaCO_3} + 2H_2O$

PRECIPITATION INVOLVING SULPHATES

(7) Sodium carbonate (soda ash) $Na_2CO_3 + \mathit{CaSO_4} = \mathbf{CaCO_3} + Na_2SO_4$
(8) Hydrated lime and sodium carbonate
$Ca(OH)_2 + Na_2CO_3 + \mathit{MgSO_4} = \mathbf{CaCO_3} + \mathbf{Mg(OH)_2} + Na_2SO_4$

PRECIPITATION INVOLVING CHLORIDES (OR NITRATES, ETC.)

(9) Sodium carbonate $Na_2CO_3 + \mathit{CaCl_2} = \mathbf{CaCO_3} + 2NaCl$
(10) Hydrated lime and sodium carbonate
$Ca(OH)_2 + Na_2CO_3 + \mathit{MgCl_2} = \mathbf{CaCO_3} + \mathbf{Mg(OH)_2} + 2NaCl$

PRECIPITATION INVOLVING IRON AND MANGANESE

(11) Aeration $\mathit{4Fe(OH)_2} + 4H_2O + O_2 = \mathbf{4Fe(OH)_3} + 2H_2O$
(12) Aeration $\mathit{4FeCO_3} + 6H_2O + O_2 = \mathbf{4Fe(OH)_3} + 4CO_2$
(13) Aeration $\mathit{2Mn(OH)_2} + 2H_2O + O_2 = \mathbf{2Mn(OH)_4}$

* Not a precipitation reaction.

Undesirable compounds to be removed, in italics; insoluble compounds, precipitated, in bold face.

Hardness (and acidity) in whatever form are usually measured and reported in terms of calcium carbonate (molecular weight 100). Hence dosage or concentrations of any of the following reagents, in parts per million (or grains per gallon), equivalent to their respective combining weights, as indicated, will react with 100 parts per million (or grains per gallon) of hardness in any of the afore-mentioned reaction equations. Since calcium carbonate is a bivalent compound, the combining weights are the same as the molecular weights for all other bivalent compounds and twice the molecular weight in the single instance of the monovalent sodium hydroxide.

Reagent	Combining Weights
Lime, calcium oxide, CaO	56
Hydrated lime, calcium hydroxide, $Ca(OH)_2$	74
Sodium carbonate, soda ash, Na_2CO_3	106
Sodium hydroxide, $NaOH$	80

ION EXCHANGE

Basic Principle. A type of chemical reaction, somewhat different from any discussed heretofore, is that known as *base exchange* or preferably *ion exchange*. It is employed primarily in water softening. The reagent used is generally known as a *zeolite* although recent developments have extended the range of useful reagents to a point where the term zeolite is somewhat inappropriate.

In mineralogy the zeolites constitute a family of double or triple hydrous silicates of a trivalent base, usually ferric iron or aluminum, and an alkali or alkaline earth base, or both. Unlike chemical compounds in general, certain of the zeolites have a variable composition which may be represented as

$$(Na, K, Ca, Mg)\ Al\ (SiO_4)_n : (H_2O)_m$$

The first group of bases, including also other alkalies and alkaline earths, and even ammonia, are interchangeable, and the final composition of the mineral represents an equilibrium condition with the surrounding waters. When it is brought into contact with another water containing an excess of one of the equilibrium group, say calcium, there is a shifting of the equilibrium conditions resulting in the absorption of calcium and the freeing of an equivalent quantity of one of the alkali bases.

Some of the naturally occurring zeolites are employed in water softening, and others of quite similar properties are made artificially. The advantage of the synthetic preparations is that they can be made with various properties for special purposes. It is customary to abbreviate the nonspecific portion of the zeolite to the letter *Z*, so that the ion exchange reactions are represented by:

$$\left.\begin{array}{l}Ca(HCO_3)_2\\ CaSO_4\\ CaCl_2\end{array}\right\} + Na_2Z = CaZ + \left\{\begin{array}{l}2NaHCO_3\\ Na_2SO_4\\ 2NaCl\end{array}\right.$$

$$\left.\begin{array}{l}Mg(HCO_3)_2\\ MgSO_4\\ MgCl_2\end{array}\right\} + Na_2Z = MgZ + \left\{\begin{array}{l}2NaHCO_3\\ Na_2SO_4\\ 2NaCl\end{array}\right.$$

The hardness-producing bases, calcium and magnesium, are exchanged for sodium. The exchange is rapid but requires intimate contact. Moreover the reactions are reversible. After the softening properties of the mineral have become exhausted, regeneration is accomplished by treatment with a strong solution of sodium chloride. Calcium and magnesium are removed and sodium restored.

Types of Ion Exchangers. Two types of mineral zeolites are available; the greensand, a mineral found in deposits in nature, and the synthetic products. The natural mineral is granular, nonporous, highly durable and resistant to chemical change. Its softening capacity ranges from 3000 to 6000 grains of hardness (as $CaCO_3$) per cubic foot. The synthetic zeolites are prepared from a dried gel of sodium silicate and alum. This produces a porous cake which is crushed to granular particles. The synthetic zeolites are less durable and tend to disintegrate in the acid range of pH. They possess high exchange values, 8000 to 12,000 grains of hardness per cubic foot.

In addition to the mineral zeolites, synthetic, organic, cation exchangers are available. They are prepared from organic substances such as tannins, wood, or lignins, by treatment with acids, to form an insoluble complex, designated ZH_2. These organic substances are capable of removing *all* cations including Na^+ and K^+, according to the following typical reactions:

$$\left.\begin{array}{r}CaSO_4\\ 2NaCl\end{array}\right\} + ZH_2 = \left.\begin{array}{l}CaZ\\ Na_2Z\end{array}\right\} + \left\{\begin{array}{l}H_2SO_4\\ 2HCL\end{array}\right.$$

Complementary to these cation exchangers are the anion absorbers, likewise synthetic organic compounds, which are capable of absorbing the acids of the foregoing reactions. A water practically equivalent to distilled water may be prepared by the successive application of these two reagents. Silica, however, is not removed. The cation exchanger may be regenerated by treatment with acid, and the anion absorber, with sodium carbonate.

In its present stage of development, complete deionization, though possible, is too expensive and complicated to be of interest in connection with municipal supplies. The principles are of interest, however, and, in special instances, of considerable importance.* As a war measure a small outfit was made available to fliers in the military forces, that would deionize sea water sufficiently to make it drinkable.

ADSORPTION

Adsorption is a physical phenomenon which simulates in some ways a chemical reaction. It is associated with boundary conditions between phases (as a liquid–solid interface) and appears to be a surface phenomenon. The adsorbed substance (adsorbate) is removed from the liquid (or gas) phase and deposited on the solid surface. Adsorption has much in common with coagulation, and it is quite possible that a satisfactory theory of coagulation will likewise clarify the mechanism of adsorption.

Self-adsorption is the phenomenon whereby a substance in solution in the liquid phase is removed by surface contact with the same substance in the solid phase. It is exemplified by the contact adsorption of manganese compounds from water (p. 538). If water containing manganese is passed through a bed of coke or stone, a deposit of manganese will gradually form on the surface of the medium, after which it is noted that the rapidity and completion of removal of manganese are greatly increased. Manganese in the solid phase, coating the stone, adsorbs the manganese in the liquid phase when intimate contact is provided.

Induced adsorption involves the introduction of a solid adsorption medium upon which matter in the liquid phase can accumulate. Activated carbon is an example. The water can be passed through the medium, or the medium can be swept through the water by agitation. Induced adsorption is employed primarily for the removal of tastes and odors, but it is not thus limited.

It is here that adsorption most nearly approaches coagulation. Such phenomena as the removal of color by aluminum hydroxide appear to be connecting links between the two.

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* F. Bachman, *J. Am. Water Works Assoc.*, **36**, 876, 1944.

THE ADSORPTION EQUILIBRIUM. Quantitative studies of adsorption are possible through the Freundlich adsorption equation:

$$\frac{X}{M} = kC^{\frac{1}{n}}$$

in which X is the weight of adsorbed substance, M the weight of adsorbing medium, C the concentration of adsorbate remaining in the water, and k and n are constants related to the concentration units employed, the type of adsorption medium, the nature of the adsorbate, and the character of the solution medium and its temperature.

This expression indicates that the system assumes an equilibrium condition at which the concentration of adsorbate in the adsorbing medium X/M is a function of its residual concentration in the water C. This function, however, is not linear. The relation can best be analyzed by converting it to the equivalent logarithmic form:

$$\log \frac{X}{M} = \log k + \frac{1}{n} \log C$$

This is the equation of a straight line in which $1/n$ is the slope and $\log k$ the intercept on the ordinate when $\log C$ is zero ($C = 1$). The relation is indicated in Figure 84.

Applied to odor removal, the concentration C can be measured in terms of *threshold odor* (p. 298). By conducting tests at a given temperature, with various dosages of adsorbant, and measuring the threshold odors, it is possible to construct an adsorption isotherm corresponding to Figure 84. A series of similar curves for various temperatures affords a basis for predicting required dosage for any desired degree of odor removal or of permissible residual odor. This procedure also furnishes a basis for comparing the effectiveness of various adsorption media for a particular water.*

Adsorption media employed in induced adsorption of impurities are dried pulverized colloidal gels and carbon products. The activated

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* Adsorption media are known to be highly selective, that is, effective only in the adsorption of specific substances. This peculiarity makes quantitative comparisons among different waters difficult, because the nature of the odor-producing substances may vary markedly. In consequence, standardization of adsorption media is only possible for the water under test, and the results may not be applicable to another water.

carbons are superior to the gels. Charcoal, bone char and carbon deposits have long been known as adsorption media capable of removing gases and odors.

The commercial *activated carbon* products prepared under controlled conditions of carbonizing are many times superior to the older products. The activity of activated carbon is probably due to its physical structure. Its spongelike lattice affords a tremendous surface contact area. It has been estimated that one cubic inch of finely divided activated carbon has a surface area of about 20,000 square yards. Activated carbon is available in either granular form or powdered; the latter being more commonly used in municipal water treatment.

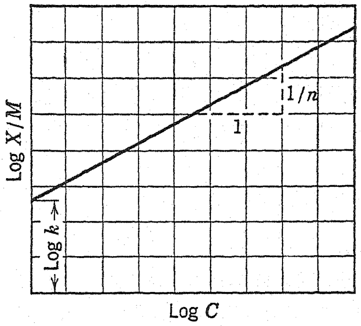

FIG. 84. Graph of Freundlich's adsorption equation.

DISINFECTION PRINCIPLES

We have seen that the most dangerous and undesirable type of pollution in a domestic water supply is that represented by organisms associated with sewage and human excreta. The presence of such organisms is indicative of the possible or probable presence of pathogenic organisms from the same sources, and the detention or destruction of pathogens at some point between the outgoing and the incoming segments of the water contact cycle is the most important single function of water supply protection.

Bacterial removal, regarded as a special case of the removal of suspended matter and without specific reference to pathogenic bacteria, is incidental to every principle of treatment thus far discussed. It accompanies sedimentation, is enhanced by coagulation, and can be carried to almost any desired degree of completeness by filtration, employing either biological or mechanical principles. It was especially characteristic of the old slow-sand water filter. At Lawrence and at Albany, reductions in bacteria, as noted on the plate count, were of the order of 98 or 99 per cent.

Complete sterilization, that is, the destruction of all life, is usually neither necessary nor practicable. With modern methods of chlorination, however, it is possible, in many situations, to approximate this ideal condition sufficiently to justify the use of the term *sterilized*. The usual and more practicable objective is the reduction of bacterial and other agencies of infection to the lowest concentration compatible with technical and financial limitations. Hence, we speak of *disinfection* rather than *sterilization* as a function of water and sewage treatment, and apply specific bacteriological criteria to measure conditions and efficiencies. Secondary objectives are reduction in the numbers of bacteria in general, more particularly those capable of multiplication in water mains with consequent development of tastes and odors, and destruction of various objectionable forms such as the slime-producing fungi in condenser waters.

THE COLIFORM INDEX. The detection of specific pathogens or disease agencies in a polluted water is, at best, a difficult procedure, and the coliform group of bacteria provides a convenient and quantitative measure of fecal pollution (p. 313). Some reservations have to be made as to the significance of this test (where the stream drains pastureland, for example) and it is a safe rule that all bacteriological data should be *interpreted* in the light of a *sanitary survey* of the watershed (see p. 275).

The application of the coliform criterion to treated waters introduces further uncertainties. In dealing with physical and mechanical means, sedimentation, coagulation, and filtration proper, there is little reason to anticipate any selective action in the removal of the various types of bacteria. Certain of the animal parasites, it is true, such as the encysted form of *Endamoeba histolytica* (amoebic dysentery), differ from the bacteria in size and specific gravity and may require special consideration.

On the other hand, treatments which depend upon biological reactions call for caution in the general application of the coliform criterion as a measure of disinfection. It may not be presumed, for example, without adequate evidence, that the organism *Eberthella typhosa,* the infectious agent in typhoid fever, will respond to the destructive action of the soil in the slow-sand filter or to the germicidal action of chlorine exactly as do the coliforms. In this particular instance there are, fortunately, good experimental data to indicate that the typhoid organisms are, in general, somewhat less resistant than are the coliforms to these treatments as well as to natural death rates and antagonistic conditions in polluted streams.*

The virus of poliomyelitis appears to be no more resistant to free chlorine residuals than is *Escherichia coli*† whereas the cysts of *Endamoeba histolytica,* the causative agent in amoebic dysentery, are much more so.‡

These examples are cited merely to indicate the weakness of the single coliform index as a general criterion and the need of more experimental work in this field. On the other hand, it must be emphasized that a remarkable record has been made in the reduction of enteric diseases through water purification, controlled as to bacterial removal by the coliform index, which apparently possesses a wide margin of safety.

CHLORINATION

The use of chlorine and its compounds in the disinfection of water has been developed so successfully that it has become the outstanding process of disinfection and today occupies the field almost exclusively. This has been due to a combination of circumstances chief of which are the simplicity, economy, and effectiveness of chlorination; but it should not be overlooked that these are not merely inherent characteristics. They have required development, extensive research, and the investment of time and capital.§

Reactions between Chlorine and Water. When elementary chlorine is dissolved in water it reacts in the following manner:

$$Cl_2 + H_2O \leftrightharpoons HOCl + HCl$$

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* R. W. Kerr and C. T. Butterfield, *U. S. Pub. Health Service, Pub. Health Repts,* **58**, 589, 1943.

C. T. Butterfield et al., *op. cit.,* 1837.

E. Wattie and C. T. Butterfield, *op. cit.,* **59**, 1661, 1944.

C. T. Butterfield and E. Wattie, *op. cit.,* **61**, 157, 1946.

Under certain limited conditions (*pH* 7 or less, time of exposure 5 minutes or less, and chlorine dosage 0.04 part per million or less), Butterfield and Wattie found *Eberthella typhosa* slightly more resistant to chlorination than *Escherichia coli,* but *Aerobacter aerogenes,* a prominent member of the coliform group, still more resistant than either.

† G. M. Ridenour and R. S. Ingols, *Am. J. Pub. Health,* **36**, 639, 1946.

‡ G. M. Fair and S. L. Chang, *J. Am. Water Works Assoc.,* **33**, 1705, 1941.

§ It is but a just tribute to state that to C. F. Wallace and M. F. Tiernan, pioneers in this field, and to the scientific staff which has become the Wallace and Tiernan organization, is due, in major part, the credit for the continuous development which has taken place in chlorination procedures.

Chlorine and water form hypochlorous and hydrochloric acids. This is an example of a *reversible reaction*. It represents two opposing reactions each with a certain driving force, the one pushing toward the right, the other, toward the left.

Just as with a balance, under the influence of two opposing weights, this system finds its *equilibrium,* a condition determined by the relative concentrations of the reaction components on the two sides. Addition of weight to the one pan or subtraction from the other brings the system to a new equilibrium condition.

This type of equilibrium is expressed by the relation:

$$\frac{[HOCl] \times [HCl]}{[Cl_2]} = K$$

the brackets indicating concentrations of the respective substances, and K, the equilibrium constant.

Addition of chlorine or subtraction of acid (addition of alkali) move the reaction to the right whereas loss of chlorine or addition of acid move it to the left.

The free acids are further modified by dissociation,

$$HCl \rightleftharpoons H^+ + Cl^-;\ HOCl \rightleftharpoons H^+ + OCl^-$$

likewise reversible and reaching an equilibrium determined largely by the "strength" of the acid and its concentration. Hydrochloric acid, a "strong" acid is almost completely dissociated in dilute solution. Hypochlorous acid is "weak"; its dissociation is controlled largely by the presence of H^+ and OH^- ions from other sources, that is by the pH of the water.

In the dilute solutions with which we deal in the treatment of waters, the hydrolysis of chlorine goes practically to completion. There is only a negligible concentration of molecular chlorine present under these circumstances. It is to be noted, however, that any secondary reaction, capable of removing chlorine from solution, will proceed continuously, the hydrolytic reaction proceeding to the left with the removal of chlorine from that side.

The value of the dissociation constant for hypochlorous acid has not been very satisfactorily determined, but various determinations indicate that the fraction of total acid dissociated increases progressively from the region of 10 per cent at pH 6.5 to about 50 per cent at pH 7.5 and 90 per cent at pH 8.65.

CHLORINE AND ORGANIC MATTER. Chlorine reacts with substances such as phenol and ammonia to form chlorine-substitution or chlorinated products, chlorophenol and chloramines.

$$C_6H_5OH + Cl_2 = C_6H_4OHCl + HCl \qquad (I)$$

$$NH_3 + Cl_2 = NH_2Cl + HCl \qquad (II)$$

$$NH_3 + 2Cl_2 = NHCl_2 + 2HCl \qquad (III)$$

These reactions, by withdrawing chlorine, drive the initial reaction to the left. They proceed, therefore, more rapidly in acid solution, and the reaction with ammonia also proceeds more completely. The formation of monochloramine (reaction II) takes place at *p*H values in the region of 8.5; that of the dichloramine (reaction III), at about 4.5.

In the presence of readily oxidizable matter, chlorine also reacts directly with water,

$$Cl_2 + H_2O = 2HCl + O$$

releasing nascent oxygen, a powerful oxidant. This is the reaction utilized in cotton bleaching. It proceeds most rapidly in acid solution.

THE GERMICIDAL PROPERTY OF CHLORINE. There is reason to believe that hypochlorous acid and hypochlorites are specifically toxic to bacteria in ways that are distinct from oxidation. Just what this toxic reaction is has been the subject of various speculations and theories. Some recent work, of more than usual suggestiveness, indicates that the primary reaction is one between chlorine and a certain enzyme essential for bacterial reproduction.*

In the absence of organic matter capable of oxidation or of chlorination, the germicidal reaction proceeds more rapidly with increasing hydrogen ion concentration; that is, with more undissociated hypochlorous acid.† This suggests a specific reaction, possibly with the amine end chains which characterize protein molecules.

In the presence of oxidizable organic matter, acidity also speeds up the reactions of chlorination and oxidation. This reduces the chlorine concentration to the detriment of the germicidal reaction.

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* D. E. Green and P. K. Stumpf, *J. Am. Water Works Assoc.*, **38**, 1301, 1946.

† C. T. Butterfield *et al.*, *U. S. Pub. Health Service. Pub. Health Rept.*, **58**, 1837, 1943.

Thus the two types of reaction, oxidative and germicidal, are somewhat antagonistic; but they are also selectively affected by acidity so that, whereas both are speeded up in the more acid and retarded in the more alkaline water, there is a distinct differential in favor of disinfection in solutions that are somewhat alkaline. Both reactions are retarded in excessively alkaline waters. At *p*H 10 or more the disinfection reaction almost ceases.

The reactions of *calcium hypochlorite* provide further evidence of selective action. This compound, the bleaching and germicidal agent in commercial bleaching powder, dissociates upon solution as follows:

$$Ca(OCl)_2 \rightleftharpoons Ca^{++} + 2OCl^-$$

In water, free from excess of organic matter, this compound is as effective a germicide as is free chlorine. In treating sewage, however, or a water containing much organic matter, the more alkaline solution conserves the bactericidal property by slowing down the competing reactions. In the early work on sewage chlorination* it was found that the death rate became slower, a longer time of contact was required, but net reductions were greater with the increasing addition of lime. An alternative explanation of the apparent conserving power of alkalinity would bring it into harmony with what is now known concerning the reactions of the chloramines.

At times highly organic waters, which have yielded excessive tastes and odors upon chlorination, have been treated first with ammonia and then with chlorine in proper proportions to react as follows:

$$Cl_2 + NH_3 \rightleftharpoons NH_2Cl + HCl$$

This reaction between chlorine and ammonia is the equivalent of the more complex reactions between chlorine and organic amines or amino acids. By employment of this reaction to anticipate the more complex one, a disinfectant, monochloramine, is produced which, the reaction being reversible, slowly yields chlorine and hypochlorous acid to the solution. Chloramine is a slower and, to that extent, a less active germicide than free chlorine. But in certain highly organic waters it conserves chlorine and by eliminating the complex organic reaction lessens the production of tastes and odors which was the principal purpose of its substitution.†

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* E. B. Phelps, *U. S. Geol. Survey Water Supply Paper* **229**, 1909.

† A. E. Griffin, *Am. J. Pub. Health*, **27**, 1226, 1937.

Available Chlorine. Commercial bleaching powder has always been marketed upon the basis of its *available chlorine*. This term has frequently been misinterpreted and without some definite statement of its true meaning is likely to be confusing. A more complete statement of its significance would be *oxidizing power expressed in terms of chlorine*. The chemical determination of the available chlorine of a substance is based upon its reaction with potassium iodide in acid solution and subsequent titration of the iodine released. The available chlorine is then the chlorine equivalent of this iodine. Thus, with sodium hypochlorite, the reaction is

$$\mathrm{NaOCl + 2HCl + 2KI = NaCl + 2KCl + I_2 + H_2O}$$

The iodine liberated, and hence the available chlorine, is twice the equivalent of the chlorine actually present in the hypochlorite.

Expressed in the customary form of percentage composition, sodium hypochlorite has a total chlorine content of 47.7 per cent and an available chlorine of 95.4 per cent. Similarly, a theoretical pure calcium hypochlorite [$\mathrm{Ca\,(OCl)_2}$] would contain 49.6 per cent of chlorine and an available chlorine content of 99.2 per cent; some of the commercial forms of calcium hypochlorite run as high as 70 per cent of available chlorine.

It is sometimes said that the term available chlorine is a misnomer. This is not true. It correctly expresses the chemical facts and is sanctioned by long usage; it merely requires correct definition for its proper understanding and use. If it be recalled that in the reaction,

$$\mathrm{Cl_2 + H_2O \rightleftharpoons HCl + HOCl}$$

all the initial chlorine is *available* and that the hypochlorous acid HOCl is the only active bleaching or disinfecting agent and must have all the available chlorine of $\mathrm{Cl_2}$, the meaning of the term available chlorine will be readily appreciated.

Chlorine Demand and Chlorine Residuals. Because organic matter in water reacts with and thereby utilizes chlorine, a water, with its organic impurities, may be said to have a *chlorine demand*. The germicidal reactions proceed simultaneously with the reactions with organic impurities, but it is a good working rule in practice to assume that the chlorine demand must be satisfied before germicidal action begins. More benefit will be derived from this useful rule if its theoretical weakness is appreciated.

In the first place, the so-called *demand* is a continuing reaction, and its determination after 10 minutes or other limited time of contact is only a first approximation. Again, this demand is a concentration function and is enhanced by adding more chlorine at the start. This is definitely shown in the breakpoint procedure (p. 482).

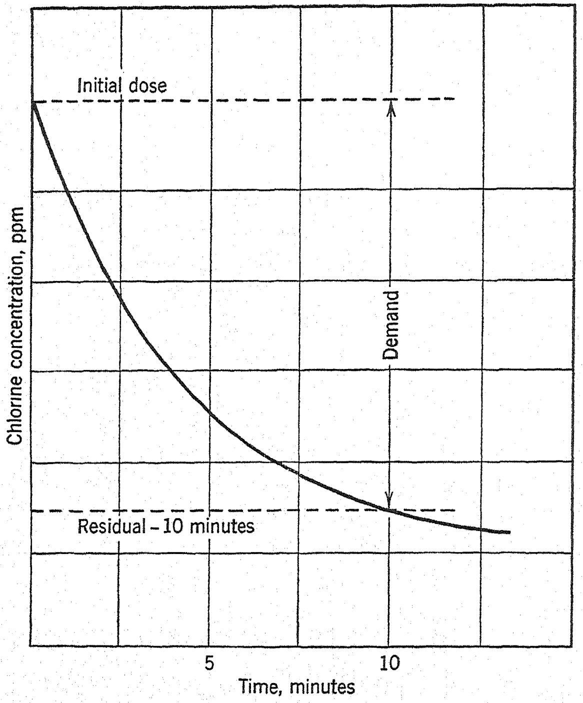

Fig. 85. Chlorine demand and chlorine residual.

The demand is also a function of the *p*H and the temperature of the water. Finally the germicidal action does not in fact lag until the demand is satisfied but proceeds simultaneously. This, too, is a time-concentration function. The greater the concentration of chlorine (other things being equal) the higher the bacterial death rate. The entire situation may best be illustrated in graphic form.

In Figure 85 there is shown a hypothetical time-concentration curve of the chlorine demand. Ten minutes after the application of the initial dose, the *residual chlorine* is measured.* The loss is the indicated 10-minute demand. During the interval the bacteria have been subjected to the influence of chlorine, first, for a moment, to the full strength, and, then, for succeeding short periods, to concentrations of decreasing strength. If the ordinates of this curve were in terms of actual speed of disinfection rather than concentration, then the area of the curve (product of speed by time) would represent the total disinfection. This is, in fact, approximately true, as there is a nearly linear relation between speed (inverse of time to disinfect) and concentration.

Figure 86 indicates a hypothetical relation between the chlorine demands of a water and a sewage. The initial doses and the demand curves have been so drawn as to include approximately equal areas. Other controlling conditions, such as *p*H and temperature, being equalized, it would be expected that the resultant bacterial kill would be of about the same relative magnitude (per cent) in the two cases. The rates of the reactions, however, are quite different; a 50 per cent kill being accomplished in about 6 minutes in the sewage as compared with about 45 minutes in the water.

It may be concluded from the foregoing that in a strict sense, there is no true interference between the organic matter, with its chlorine demand, and the bactericidal reaction. The bacteria are influenced by the existing concentration and the time of exposure. The chlorine demand of the organic matter reduces the concentration progressively and thus defines the time–concentration area which is an approximate measure of the total kill.

This discussion has been somewhat oversimplified by the tacit assumption that the chemical nature of the apparent demand and the bactericidal power of the resultant residuals are the same in all waters or in the same water at all times. This assumption is not always valid. In the presence of ammoniacal nitrogen part or even all of the measured residual may be in the form of chloramines.

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* The determination of the small concentrations of chlorine involved in these reactions is conveniently made with the aid of a *comparator,* of which there are several satisfactory types on the market. The reagent *orthotolidine* added to the water under test, reacts with chlorine to produce a bright yellow color ranging from greenish yellow in low concentrations to orange, as the concentration increases. The comparator is provided with a set of sealed tubes containing colored waters or with a set of colored glass disks corresponding to the colors produced by the various concentrations of chlorine, and the sample under test is compared with these by matching colors.

The nature of this complication is described in more detail under the discussion of the breakpoint process. It will serve for the present to note that the bactericidal power of any given residual is lessened in proportion to the fraction of that residual that exists as chloramine and that this effect increases progressively with increasing pH (increasing alkalinity).

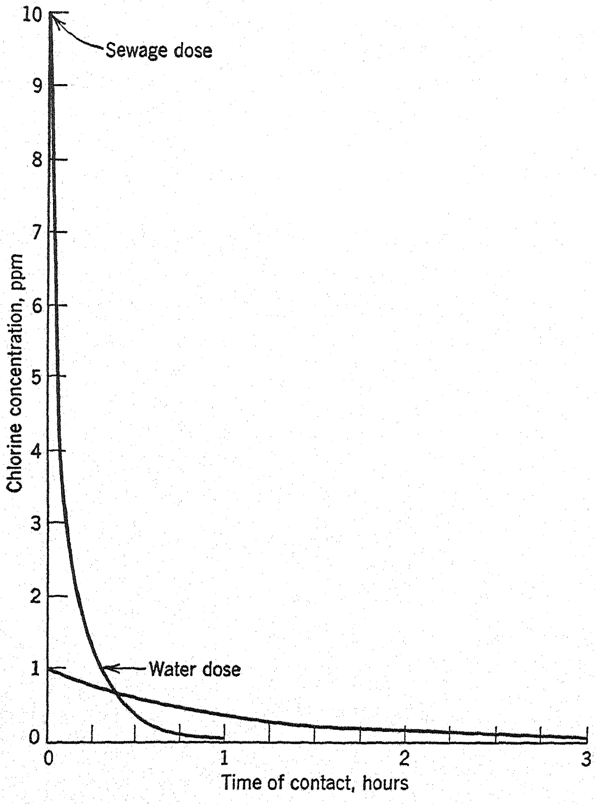

FIG. 86. Time–concentration areas.

Sewage requires more chlorine than water for disinfection and waters differ among themselves in a similar manner. This difference is qualitative as well as quantitative, being related to the nature of the organic matter, especially its nitrogenous nature, to the hydrogen ion concentration, to the temperature, and probably to other physical and chemical factors.

It is a common practice to control disinfection on the basis of a *residual chlorine* value. The determination of the residual may be made after 10 minutes, 30 minutes, or any other convenient interval from the time of chlorine application, according to the plan and piping layout. It is usually possible to determine, experimentally, what residual is required for satisfactory disinfection of the water under treatment. But, for the reasons set forth, it is not possible to establish any general rule or to set up any stated residual as representing satisfactory disinfection in general and for all waters. In fact, a very useful degree of killing, short, however, of the usual requirements in water, can be brought about in sewage by the application of chlorine in quantities less than sufficient to satisfy the demand.

Control of the process by residual chlorine, therefore, must finally rest upon the results of bacteriological examinations. Experience with a given water generally indicates the appropriate residual for that water and its changes with season and other variables. With this information in hand the operator will find the residual test a convenient short cut in routine operation. He will be most unwise, however, if he overlooks the wholly artificial character of both the demand and the residual and accepts them as fixed and measurable characteristics of the water under treatment.

BREAKPOINT CHLORINATION. These matters of demands and residuals have been greatly clarified, and an entirely new point of approach has been indicated by studies which led to the introduction of a new water characteristic called its chlorine breakpoint.* If, to a water, having no chlorine demand, one adds chlorine in stated amounts, the residuals will equal the additions throughout the scale. The applied-residual curve (curve *A,* Figure 87) is a 45-degree line from the origin. On the other hand, in a water with a chlorine demand, a residual curve similar to the first arm of curve *B* will develop. This represents the situation after some arbitrary time of contact with the water, say 10 minutes. The difference between curves *A* and *B* represents the (10-minute) demand. A longer time of contact will lower the residual values and correspondingly increase the indicated demand. Thus the so-called *demand* is a somewhat fictitious value, associated, it is true, with water quality, but also variable with chlorine concentration and with time.

The residual, as thus measured, increases progressively, with

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* A. E. Griffin, *J. Am. Water Works Assoc.,* **31**, 2121, 1939.

increasing additions of chlorine, but it does not mount so rapidly as in the no-demand curve *A*. The difference between curves *A* and *B* (the demand during 10 minutes) is separately plotted as curve *C*.

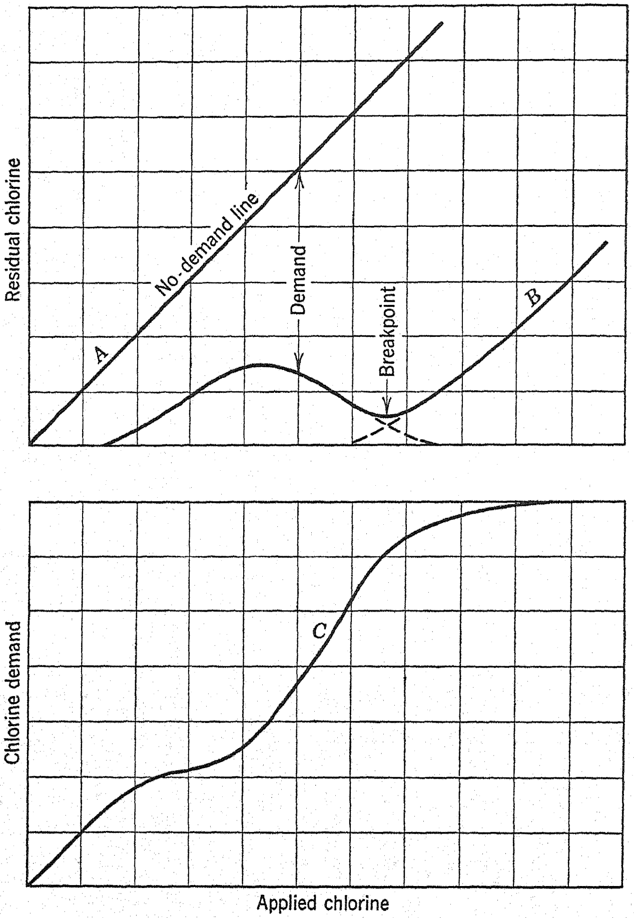

FIG. 87. The chlorine breakpoint.

The demand increases progressively with increasing dosage, but it tends to approach an upper limit.

These indicated demands represent the utilization of chlorine in various reactions with the organic matter present. In their natural state such substances as leaf extract, materials leached from the soil, and the products of microscopic plant and animal life possess odors which are sometimes objectionable. Many of these substances, particularly those of phenolic or of amino nature, develop much stronger tastes and odors when chlorinated with the customary dosages, represented in the "hump" of the residual curve. This situation, in the past, has tended to limit chlorine dosages on the theory that less chlorine would produce less odor. The natural response to any general complaint of tastes and odors has been to lower the dosage, often at the expense of effective disinfection.

Some years ago it was noted by various investigators that excessive doses of chlorine, *superchlorination* as it was then called, followed by dechlorination with sulphur dioxide or equivalent reducing agent, would generally greatly reduce or even eliminate odors that had developed under the ordinary treatment. Later it was discovered that, if these high dosages, necessary to destroy odors were added step by step in a laboratory test, a point was reached at which the residuals actually decreased with increasing dosage (curve *B*).* This clearly indicated an increasing utilization of the applied chlorine to satisfy an increasing demand at the higher concentrations (curve *C*). Beyond the point of minimum residual (the *breakpoint*) the residual again increased and tended, with time, to approach the 45-degree line of the no-demand water.

This illustration is a typical and somewhat idealized breakpoint curve to illustrate the principal facts. It is generally modified in actual practice and may even be completely disguised in certain waters, but it is believed that the deductions to be drawn from the typical curve are of general applicability.

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* Concerning the early appreciation of the significance of this phenomenon A. E. Griffin, of the Wallace and Tiernan organization, writes me that in 1939, in company with H. A. Faber, of the Chlorine Institute, he ran some tests upon a surface water to investigate a statement made earlier by C. K. Calvert of the Indianapolis Water Company to the effect that chlorine residuals declined as chlorine dosage was increased.

"Faber and I repeated this experiment on three successive days just to be sure that we had not made a mistake, because, on the water used, the residual dropped to zero upon the application of 26 ppm, whereas the residual had been 8 ppm at the 18-ppm dosage. We further noticed that, at the top of the hump, the water was very odoriferous, whereas at the point where the residual disappeared odors were nonexistent." After running a long series of tests upon a great variety of waters throughout the country Griffin concluded that ". . . only those waters containing appreciable amounts of free ammonia produced a typical ascending and descending curve upon the addition of chlorine in increasing quantities." E.B.P.

It is quite evident that a change in the nature of the reaction has occurred at chlorine concentrations corresponding to the high point of the "hump" in curve *B*. It is now believed* that the reactions taking place are somewhat as follows.

At the lower concentrations, chlorine is consumed by reaction with organic matter, including ammonia which may be taken as typical. Chloramines and similar substitution products are formed. Many of these possess objectionable odors.

Chlorination at higher dosages completes these reactions. The end products do not contribute to taste or odor, and, unlike the products of the first stage they do not react with *o*-tolidine to indicate a residual chlorine. Both ammonia and chlorine disappear in the process, as such.

Thus, the residual decreases with the addition of chlorine. This reaction goes on to completion as suggested in the dotted continuation of the curve. At the same time, a *free chlorine* residual begins to appear (upward dotted curve). At the *breakpoint* the measured residual is at a minimum and is due to the two forms, chloramines and free chlorine, in about equal proportions. At later stages, the residual represents only free chlorine.

In confirmation of this view is the fact that the chlorinated amines react slowly with the *o*-tolidine test reagent, so the full color due to the total residual develops gradually up to about 5 minutes, whereas free chlorine reacts instantly. If, therefore, two readings are made, at once and after 5 minutes, they will indicate the free-chlorine residual and the total residual, respectively. It is found, as a practical matter of control, that the true break-point lies at the point in the ascending dosage curve at which free chlorine predominates. Free chlorine residuals from 85 to 100 per cent of the total are recommended for plant control.

ADVANTAGES OF BREAKPOINT CHLORINATION. One of the most serious handicaps associated with chlorination of water has been the development of tastes and odors. Organic matter, in general, and especially decaying organic matters contain phenolic and amine groupings that are likely to yield increased taste and odor upon chlorination. It is not the least of the advantages of the breakpoint process that it reduces or eliminates this cause of complaint. This

* A. E. Griffin and N. S. Chamberlin, *J. New Engl. Water Works Assoc.*, **55**, 371, 1941.

A. E. Griffin, *J. Am. Water Works Assoc.*, **33**, 2088, 1941.

does not refer to the ordinary rather sweetish and not unpleasant taste of the chlorine itself. This is never so objectionable to the consumer, and he should be educated to expect and approve of it as a measure of his protection. If excessive, it may be removed by dechlorination with sulphur dioxide, a process that has been employed in connection with superchlorination where a large excess of chlorine is applied.

Taste and odor control first attracted attention among the advantages of breakpoint chlorination but a far more significant result, from the public health point of view, is the greater completeness and reliability of the disinfection process itself. A distinction was made in the introductory portion of this section between disinfection and sterilization. The delicate matter of the interpretation of *E. coli* findings was also discussed and might have been treated in more detail with regard to *atypical forms, slow gas formers,* and other uncertainties that have given the bacteriologist much concern. It is also true that we have hitherto accepted quite complacently the presence of relatively high numbers of the *common water bacteria,* which, although nonpathogenic, are known to gather and grow in the distribution system and often to cause musty and other tastes of organic decay, and to upset the nice balance involved in *p*H adjustment for corrosion control (p. 294).

The high concentrations of chlorine that may be employed in the breakpoint process frequently achieve a true sterilization and in all cases result in a great reduction of the bacteria commonly reported as *total count.* Of more importance, however, the successful application of the technique gives vastly greater assurance of the absence, not only of the typical coliforms under standard methods of testing and recording, but also of all those atypical forms which are being increasingly suspected of indicating waters not quite up to our total requirements.

In view of these facts it has now become customary to speak of *marginal chlorination* where the control is on the basis of chlorine residuals composed largely of chloramines, as distinguished from *breakpoint chlorination* controlled by free chlorine residuals. Much experimental work, carried out before this distinction was recognized, has now been invalidated, including, for example, the earlier reported studies of the effect of chlorination upon the virus of poliomyelitis. It is important that in the future conduct of chlorination experiments, involving survival rates of pathogenic organisms, the distinction be clearly indicated between the two types of residual values.

Some of the other benefits accruing from the maintenance of free chlorine residuals are oxidation of manganese and bleaching of color. They also assist in subsequent coagulation, keep down the growth of algae, keep filters sweet, and reduce the growth of iron bacteria and slimes in water mains.

CHLORINE DIOXIDE.* One of the newer compounds of chlorine to be employed in water treatment is chlorine dioxide (ClO_2). The chemistry and properties of this compound have long been known to chemists. Within recent years its production by methods suitable for application to water treatment has become possible owing to the commercial availability of the compound sodium chlorite, $NaClO_2$. This compound reacts with chlorine as follows:

$$2NaClO_2 + Cl_2 = 2NaCl + 2ClO_2$$

Chlorine dioxide is a powerful oxidizing agent, which fact, in accordance with the principles that have been discussed, would indicate a lessened germicidal property in the presence of organic matter. This is found to be the case. Although possessing a somewhat greater germicidal efficiency than chlorine when tested in distilled water, its greater reactivity with organic impurities reduces its value in the treatment of a polluted water. Its special value, therefore, lies in its ability to destroy the aftereffects of chlorination of highly polluted waters, requiring heavy chlorine dosages. It is particularly useful in the destruction of the chlorophenols which result from the chlorination of waters polluted with gashouse wastes or other phenol-carrying wastes. Offensive odors, probably of similar nature, may arise also, during the chlorination of waters overburdened with algae and other micro-organisms. Chlorine dioxide treatment has been successfully employed in such situations.

At present, therefore, the recommendations for the use of the chlorine dioxide treatment are to employ a sufficient degree of prechlorination to satisfy the chlorine demand and to yield the residual required to accomplish the necessary reduction of bacteria, disregarding the possibility of aftereffects, and to employ the dioxide treatment as a final step in sufficient concentration to destroy all such undesirable compounds as the chlorophenols. As employed at

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* J. F. Synan, J. D. MacMahon, and G. P. Vincent, *Water Works & Sewerage*, **91**, 423, 1944.

the plant of the city of Niagara Falls, N. Y., this combined treatment has given as satisfactory results as had been previously obtained by the use of chlorine alone, employing the breakpoint procedure, at a considerable saving in cost of chlorine and with a much simplified control procedure.

OTHER DISINFECTION PROCESSES

In addition to the various chlorination processes certain other processes have been developed and employed for the specific purpose of bacterial destruction. These are properly processes of disinfection.

Heat alone is an excellent disinfectant. Boiling the water in the home is the last and surest safeguard in the employment of a water of doubtful character. It has been publicly advised during emergencies, such as resulted from disruption of the filter plants of the Ohio River cities by floods; and, with less grace, in cities having water supplies that are subject to occasional periodic pollution.

Ozone (O_3), an allotropic form of oxygen, is an active germicide and has been employed somewhat extensively in Europe. It is made by passing air through a narrow space between insulated electrodes. A high-potential alternating current applied at the electrodes produces a silent discharge, accompanied by a blue luminescence within the air gap, and a small fraction of the atmospheric oxygen is converted to ozone. The ozonized air is bubbled through the water, or the water is sprayed into an air chamber.

Ultraviolet light is a powerful germicide when properly applied. It is produced in the Cooper–Hewitt (mercury-arc) lamp and also in open-flame arc lamps with specially prepared carbons. The mercury arc lamp, commonly seen in photographers' windows and in factory illumination, is constructed of ordinary glass, which does not transmit light of shorter wave length than about 3200 A,* whereas the maximum germicidal effect is found in the invisible ultraviolet light of wave length 2537 A. Quartz is transparent to this light, and certain of the newer glasses transmit the ultraviolet with practical efficiency.

These short-wave rays will destroy bacteria in water, but they must actually reach the bacterial cell. Any turbidity in the water shades the cells from the light, and this even applies to a heavy density of bacteria themselves. In practice, the clarified water is

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* A, the angstrom is 0.1 millimicron, or 10^{-10} meter.

passed in a very thin sheet over the front of the lamp. Ultraviolet light disinfection has useful applications in the disinfection of swimming pool waters and other small supplies. It does not, however, appear to leave any aftereffect, and thus lacks one of the chief advantages of chemical disinfection and an essential requirement in swimming pool sanitation.

Copper and *silver* ions are both highly germicidal in the absence of reacting substances. The possibilities of using copper salts were explored rather thoroughly at one time.

A process of more recent appearance and of some promise makes use of the well-known oligodynamic properties of silver. It has been found that a sufficient quantity of silver to disinfect water can be dissolved by contact with porcelain containing silver salt in its glaze. For some supplies it has been found sufficient to pass a stream of water through a chamber with small rings or spheres of this specially prepared porcelain. A more practical development is based upon the electrochemical solution of silver brought about by passing a direct current through the water to be treated, and between silver electrodes. Occasional reversal of polarity utilizes both electrodes and prevents polarization. Concentrations of the order of a few tenths part per million are frequently effective.

BIOLOGICAL PRINCIPLES

BIOCHEMICAL CHANGE

It is a characteristic of most substances in nature that they are in a continuous state of physical or chemical change. Iron rusts and granite rocks are subject to slow "weathering." In the organic world, the world of living things and their products, instability is even more conspicuous. But, whereas the changes in the mineral world usually trend toward an equilibrium condition of greater stability, the products of life processes move through a cycle characterized by two opposing types of change; the *synthetic* or upbuilding reactions trending toward instability and the *analytic* or disintegrating, restoring the materials to a more stable mineral level.

The reactions of life itself and of growth are essentially synthetic; the building of tissue and the elaboration of complex from simpler compounds. They are also *endothermic* or energy-consuming processes, and energy must be supplied to support them. We are more familiar with the analytic reactions. Wood burns in the fireplace giving out heat, an *exothermic* reaction. Oxygen is utilized in the process, and carbon dioxide and water are produced. The wood (carbon and hydrogen) has been oxidized.

Similar reactions, in reverse, took place when the tree was slowly synthesizing its body from water and carbon dioxide. It then drew upon the sun's rays for its energy requirements, for this reaction was reductive and energy-consuming. It yielded oxygen as a by-product. As much heat went into it as is now being released through combustion, and as much oxygen was then released as is now being utilized.

In common with man and the animals, the bacteria and their allies derive their essential energy intake from oxidation of previously formed organic matter. In its chemical aspects the process is similar to combustion, although it takes place at lower temperature, and energy is released, not primarily as heat, but in some rather obscure form whereby it is directly available for the life and growth of the bacteria. Reactions of this type, the oxidation of organic matter and the utilization of the energy product in life processes, are called *biochemical oxidations*. They are the basic reactions upon which many of the present-day practices for artificial treatment of water and sewage rely.

THE LAW OF DECAY

Not only is organic matter endowed with latent energy but also there are ever-present, oxidative forces tending to reduce that energy, to draw the organic matter back to the mineral level. The situation is quite comparable with that which exists when a weight is lifted to an elevated position. Energy is expended in the operation. That energy lies latent in the weight, and the force of gravity exerts a constant pull in the direction of restoration. Conditions are stable only if there is no available channel of return. If, however, the weight rests upon an inclined plane of sufficient slope, it will react to the pull of gravity and return spontaneously to its base level.

The *law of decay* is to the organic world what the law of gravity is to the physical. Matter on the higher energy plane of reduction is under stress to return to its lower oxidized plane and is restrained only by lack of a suitable channel or means. This channel is provided by any of the living organisms which can utilize the substances in question as a source of energy.

Utilization may take place in stages (chain reactions) in which the by-products of one stage constitute the raw materials of the next. Most of the biochemical reactions useful in the destruction of organic matter are of this type. They are extremely complex in nature and represent the combined activities of many diverse forms of life. It frequently happens also that the separate stages consist of one living form's becoming the food of another.

It must not be thought that reference to the food relationship in the foregoing discussion indicates that new living matter is being reconstituted quantitatively from old, a condition which would nullify any usefulness the biochemical reactions might have in the ultimate destruction of waste matter. The oxidation of food is always accompanied by a large utilization of energy in other channels than mere synthesis of new body substance. The bacteria actually convert into new bacterial bodies only a few per cent of the total food intake, the remainder going into the mere support of life. A similar wastage (from the energy viewpoint) occurs when the bacteria are eaten by protozoa and with each succeeding passage through crustacea, fish, and so on. It is this inefficient utilization of energy throughout the whole process of decay that makes the process so efficient in the disposal of waste matter by biochemical oxidation and permits it to complete that important cycle of nature whereby the stage is cleared of the settings of the act that is finished and made ready for that to come.

RELATIVE STABILITY. A more detailed examination discloses an additional distinction between decay and combustion. There is a considerable variation among the various classes of organic matter in the degree of their stability or permanence. Oak wood is relatively durable; soft pine, less so. All woods are more stable than milk or fish. These attributes are quite independent of the actual combustibility of the substances themselves.

The significance of these differences is obvious in the light of the foregoing discussion of the nature of decay. Substances like the protein of milk provide a readily available food for the bacteria; wood is less available. The nature (rapidity, completeness, end products, and the like) of the biochemical oxidation is related to the availability of the organic matter involved as a food and source of energy for the life forms engaged in its oxidation. This matter of availability, moreover, is a two-way affair. The many different kinds of bacteria have many different food requirements. There are some that even prefer cellulose (wood) to meat and some that can obtain their energy through the oxidation of such inorganic "foods" as hydrogen sulphide (H_2S), ferrous iron (Fe), ammonia (NH_3), and sulphur (S). Others thrive on a diet of crude petroleum. Thus stability is relative to the kind of bacteria and, because bacteria have their preferred environments, to the environment itself.

Chain Reactions. A consequence of this selectivity on the part of the bacteria (and the rule applies to all higher forms) is the occurrence of the chain reactions referred to previously. In the complex situations that develop in the treatment of sewage by biological agencies, the operations are not unlike those in the production line of a modern automobile factory. The material undergoing disposal passes through innumerable stages in each of which a single operation is performed. The whole sequence is "supervised" by the bacteria-eating protozoa whose chief function is to keep the population of the workers down to the level of maximum efficiency and to reduce the accumulated load of newly created organic matter (bacteria) by a second passage through a wasteful biochemical system.

A final characteristic of biochemical oxidation which distinguishes it from combustion is that the chain reactions lead to the formation of materials of ever increasing stability, but they do not go to completion. There is always a residual product, definitely combustible, but having little if any remaining energy available for bacterial growth. In the woods and fields this is the *humus,* that inert finely divided black earth which appears to be perfectly stable. It is quite probable, however, that even humus undergoes very slow oxidation under suitable conditions. The residues from the various sewage treatment processes are often of a humus-like nature, and through the various stages of treatment the organic matter is continuously improving its stability or trending toward the humus stage. Thus, it is quite possible to derive from certain processes a relatively large organic residue which, if measured chemically, represents poor efficiency; whereas, in biochemical terms, that is, in terms of the BOD, the improvement is quite satisfactory.

ENVIRONMENTS

Availability being a function of bacterial species as well as of chemical composition of the material, it is obvious that the nature and extent of any biochemical reactions taking place are related to the environmental conditions. Among these, the oxygen relations and the temperature appear to be the most important.

OXYGEN RELATIONS. That which we have termed *biochemical oxidation* is regarded by biologists from the opposite viewpoint and becomes *bacterial respiration*. Three types are distinguished, each having significance in connection with the treatment of water and sewage. They are:

Gaseous respiration (elementary oxygen).
Intermolecular respiration.
Intramolecular respiration.

Bacterial respiration (or biochemical oxidation), in general, utilizes oxygen. The three types of respiration are identified with three distinct sources of oxygen and with corresponding oxidation potential levels within the preferred environments of the respective bacterial species. Each such species has a range of oxygen potential within which it functions most advantageously. For the majority of the species this range is broad and extends across the imaginary line which separates the so-called *aerobic* and *anaerobic* conditions.* These species, able to live with or without air (in the older sense), are the so-called *facultative bacteria*. On the other hand, if the acceptable range of oxygen is well within the anaerobic range, the bacteria are known as *obligate anaerobes* and, if well within the aerobic range, as *obligate aerobes*.

GASEOUS RESPIRATION. Under aerobic conditions the water contains some dissolved oxygen gas. This is available to the bacteria for respiration just as it is to the fish and is utilized in much the same manner. The process of gaseous respiration characterizes many of the common biochemical reactions. Organic matter (food) is oxidized at the expense of the oxygen carried in the water. This relationship is of especial significance in the self-purification of streams and in the so-called oxidizing treatments of polluted water.

INTERMOLECULAR RESPIRATION. If a somewhat polluted water be supplied with some gaseous oxygen and, in addition, with some nitrate (such as $NaNO_3$) and the course of the reaction be then followed, it will be found that the free oxygen is first utilized almost completely; then the bacteria will reduce the nitrate to nitrite

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* The distinction between aerobic and anaerobic conditions, though indefinite and unscientific, is useful and will be maintained.

($NaNO_2$). The oxygen derived from this reduction is utilized by the bacteria just as was the gaseous oxygen. This is intermolecular respiration. Oxygen is withdrawn from one molecule and utilized in the oxidation of another. Obviously, the work is now being done at a lower level of oxygen potential, and the gain in energy is less by the amount involved in the reduction of the nitrate.

This is typical of many reactions whereby oxidation is enabled to proceed in the absence of free oxygen. Less energy is freed, and the oxidation, being at a lower level, does not proceed so far. In a similar manner sulphates are reduced to sulphides, a characteristic reaction in heavily polluted waters and one which provides a useful criterion of the oxygen balance in the stream. The anaerobic condition of an overloaded stream is usually accompanied by the production of hydrogen sulphide with its disagreeable odor and harmfulness to fish life and to painted structures.

INTRAMOLECULAR RESPIRATION. At a still lower level of oxygen potential other members of the anaerobic class of bacteria are able to function and to carry on oxidation for the release of energy by oxidizing one part of an organic molecule at the expense of another part. The fermentation of dextrose to alcohol (Pasteur's classic example of "life without air"), simplified of side reactions, takes the following course:

$$\underset{\text{Dextrose}}{C_6H_{12}O_6} = \underset{\text{Carbon dioxide}}{2CO_2} + \underset{\text{Alcohol}}{2C_2H_6O}$$

In the dextrose there is just enough oxygen to oxidize the hydrogen to water (6 H_2O) or just half enough to satisfy the demands of the carbon. In the products one third of the carbon has been fully oxidized at the expense of a greatly lowered oxygen ratio in the alcohol molecule. Engery is derived from this reaction to support the life and growth of the organisms performing it (yeast in this instance).* The residual products are further reduced. The reaction typifies those that go on during the *digestion* of sewage sludges and the comparable processes that take place in sludge beds deposited on river bottoms and muck beds underlying marshes.

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* Pasteur's data are of interest here to show the relative proportions of the net energy yield that go to syntheses of new living matter and to other purposes. He found that 100 parts of dextrose yielded 48.5 parts of alcohol instead of a theoretical 51.1 parts. If other by-products are neglected, this leaves a maximum utilization of only 2.6 per cent of the dextrose for the formation of new yeast cells.

Temperature Relations. In common with all life processes, the biochemical reactions are performed most advantageously within certain temperature ranges. In general, the reactions are speeded up by raising the temperature, but this merely means that their optimum temperatures are higher than those under which we normally operate. A better statement of the situation is that each specific reaction (one bacterial species acting upon one chemical species) has an optimum temperature, at which it operates at maximum velocity; above and below the optimum the velocity is reduced.

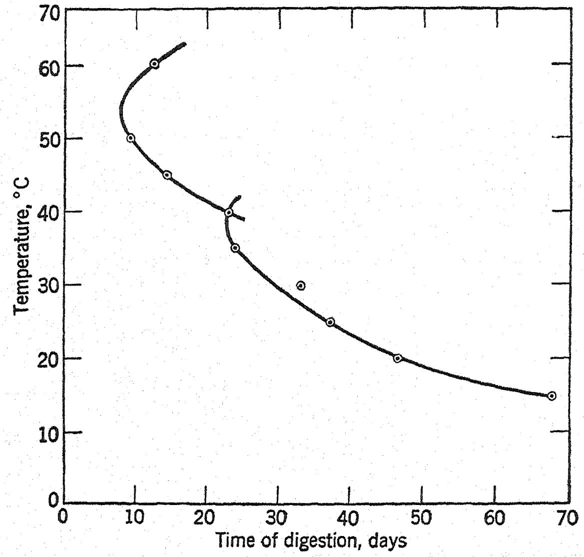

Fig. 88. Effect of temperature on the rate of sludge digestion. (Fair & Moore.)

We have seen that within ordinary operating temperatures in the laboratory and the stream the BOD reaction has a temperature coefficient of 1.047. This means that its rate is increased by 4.7 per cent for a rise of one degree (centigrade). Probably this is merely a mean value covering the many bacterial and other species involved in the reactions. At different temperatures different species are dominant.

This is indicated in the digestion of sludges resulting from the preliminary sedimentation of sewage. The reactions are speeded up 2.2-fold by increasing the temperature from 25 to 40 degrees centigrade. At about 40 degrees this particular set of reactions begins to slow down, but other reactions come into play which reach their optimum values in the neighborhood of 50 degrees, above which they, in turn, slow down* (Figure 88).

SOME PHYSIOLOGICAL ASPECTS

To inquire in any detail into the physiology of bacterial respiration and metabolism would lead beyond our present interests, but it may prove helpful to outline the mechanisms by means of which the bacteria secure, absorb, and digest their food. The bacterial cell consists of a small mass of cellular substance, somewhat differentiated into granules and other bodies, distinguishable by differences in density and by staining reactions. The cell mass is enclosed within a membrane which serves to contain the semiliquid contents and to maintain the shape of the cell, which may be spherical, rod-shaped, or curved like a sausage.

The food of the organism must pass through this outer membrane. This passage is probably accomplished by pure osmotic diffusion, although, possibly, certain more specific reactions are involved. In any case, only foods in solution can thus be utilized.

ENZYMES. Much of the work of absorption and digestion of foods, among the bacteria, as among the higher animals, is performed by enzymes, a class of highly organized proteins. It is characteristic of the enzymes that they act as intermediate agencies, or go-betweens; they take part in reactions in an early stage and are later released and made available for continuous repetitions of the process. Thus, they are of the nature of chemical catalysts. The enzymes are highly specialized, each adapted to a specific task. With regard to the localization of their actions, they may be classified as *intercellular* and *extracellular*.

The first stage in the digestion and utilization of an insoluble food substance is to render it soluble and diffusible. In the human alimentary tract this is accomplished by pepsin, trypsin, and other enzymes of digestion excreted through special organs into the tract. In a similar manner, the bacteria excrete *extracellular enzymes* into the surrounding area to prepare the food for absorption through the cell membranes. The extracellular reactions constitute an important part of those processes which we term *sludge digestion*.

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* G. M. Fair and E. W. Moore, *Sewage Works J.*, **9**, 3, 1937.

The result is partial liquefication of insoluble sludges. The utilization of insoluble organic matter in any of the biochemical oxidations is dependent upon primary solution.

The *intercellular enzymes* stimulate the truly oxidative reactions which accompany bacterial respiration and which, for obvious reasons, are carried on within the cell. Otherwise, the bacteria could make no use of the energy released.

HABITATS

The various bacterial species with their associated communities of plant and animal life each have their preferred habitats. Many forms are ubiquitous; others are to be found only in strictly limited environments. The so-called *processes* of treatment, whether of water or of sewage, insofar as they rely upon biochemical reactions, are merely engineering expressions of these favorable habitats, developed empirically by trial and error, and according to the specific needs of each of the widely varying situations.

AEROBIC HABITATS. Those processes which bring about oxidation of organic matter rely for the most part upon the so-called *aerobes,* the air-breathing bacteria. The process will operate satisfactorily only when the three essentials, the accumulated biological growth, the food supply, and oxygen, are brought together in a suitable engineering structure or housing. Special attention must be given, therefore, to the air supply, either by the use of filters, so constructed and operated that air circulates through the filter medium (slow-sand and trickling filters), by forced aeration through the accumulated organic growth (activated sludge), or by other means. The biological growth, in the aerobic habitat, usually assumes the form of gelatinous masses, the so-called zooglea. We refer to these masses as bacterial, and it is true that the bacteria constitute the labor forces upon which the work of ultimate resolution devolves. The zoogleal masses, however, are actually communities made up of a diverse fauna and flora, and it is probable that many of the species found therein perform essential duties. It is known, for example, that the protozoa, microscopic animals, are most helpful, if not essential, in preventing overdevelopment of the bacterial populations. In all likelihood, the entire community works together as a balanced aquarium, each performing a useful part of the total accomplishment.

In the filters these masses develop as slimes upon the stone or sand surfaces. No better description can be found of them, regarded as living material, than was given by one of our earliest biological students of water and sewage treatment, the late William T. Sedgwick, biologist of the Massachusetts State Board of Health at its now famous Lawrence Experiment Station:

> Besides the bacteria found in the materials of which the filters are made, the microscope reveals a quantity of brown flakes, or flecks, of amorphous matter, which appear to be largely a peculiar form of bacterial jelly, mycoderm or zooglea. This is so constant throughout all the tanks (filters), and apparently so characteristic, that it demands special consideration. From what has been said above, it is evident that it is the only organic material, visible with the microscope, which occurs throughout the tanks, from top to bottom. It cannot be regarded as an accidental accumulation of debris, since it is essentially uniform in character, and is attached to the sand grains as if it had formed there rather than as if it had been accidentally detained. From its connection with the sand grains and its microscopical appearance, there is no reason to doubt that it is, for the most part at any rate, the peculiar gelatinous condition of bacterial development known as mycoderm or zooglea. We . . . have some indications that a sand filter is ineffective until this zooglea has begun to form, although it appears that a mature filter is not a mechanical purifier, but rather a respiratory mechanism. The analogy of fermentation by yeast, in which a large amount of chemical change is effected by a relatively small amount of yeast, naturally suggests itself inasmuch as the chemical changes effected by a mature filter are enormous and out of all obvious proportion to the discoverable changes in the zooglea. The analogy is entirely reasonable, since the fermentations produced by bacteria are known to resemble closely those produced by yeast. *

ANAEROBIC HABITATS. The biochemical reactions involved in sludge digestion in the septic tank are performed by the *anaerobes,* bacteria capable of functioning through intermolecular respiration. Although oxidation, in its broad sense, is the basis of these reactions and the means whereby the bacteria obtain their required energy, the fact remains that the changes are intermolecular; there is no *net oxidation* from the point of view of the total system. Only when there is a loss of such nonavailable organic matter as hydrogen or methane gas (having high combustion values but not usable by the bacteria as food), is there any net loss in the total BOD requirements of the liquid. The function of anaerobic treatments is liquefaction

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* Mass. State Board Health, *Purification of Water and Sewage,* Boston, 1890.

and gasification to such an extent that the ultimate solid organic residues are of increased density and relatively stable so that they can be disposed of without nuisance.

The associated biological communities are as complex as those in the aerobic communities and, no doubt, as many or more specific reactions are involved in the whole process. The work is done in sludge digestion chambers or tanks with provision for the escape of the resultant gases which, incidentally, have utilizable fuel value. A helpful adjunct is artificial heating, which speeds up the reaction and shortens the time required for its completion.

STREAM HABITATS. In the stream the normal habitat is aerobic, and the reactions of self-purification are akin to those taking place in artificial treatments involving oxidation. In a heavily polluted stream, however, in which the available natural supply of dissolved oxygen is unable to meet the demands of the biochemical activity, anaerobic conditions may be established, and the stream then resembles a septic tank. This oxygen relation is in fact the criterion of safe loading and proper utilization of a stream's oxygen assets (p. 405).

Finally, there is always a condition on the bottom of sluggish streams, as well as in bogs and marshes, somewhat intermediate between the aerobic conditions of a moderately polluted stream and the anaerobic conditions of one that is overloaded. This situation has been described by Fair* and his associates as one of *benthal* decomposition. It deals with the exceedingly slow and long-time decomposition of the residual organic matter after the first stage of intense activity, which we know as sludge digestion, has been worked out. Under benthal conditions, there is slow inward diffusion of dissolved oxygen and equally slow outward diffusion of soluble products, together with the escape of highly reduced gases, particularly methane (CH_4).

REFERENCES

A. M. BUSWELL, *The Chemistry of Water and Sewage Treatment,* Chemical Catalog Co., New York, 1928.

The principles discussed in this chapter are dealt with in the literature as applied to the various treatments. References therefore are listed at the ends of the appropriate chapters.

The student should keep himself abreast of research work and recent

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* G. M. Fair, E. W. Moore, and H. A. Thomas, *Sewage Works J.*, 13, 270, 756.

developments in the art through the current journals and other periodic literature. Especially noteworthy are:

Journal of the American Water Works Association.

Sewage Works Journal, Federation of Sewage Works Associations.

Journal of the New England Water Works Association.

Transactions, American Society of Civil Engineers.

Americal Journal of Public Health, American Public Health Association.

There are also a number of excellent trade magazines which constitute essential parts of the standard literature.

CHAPTER 14

TREATMENT OF POLLUTED WATERS

DOMESTIC WATER SUPPLY

The purpose of treatment, in general, is to reduce harmful and objectionable polluting substances to limits that are satisfactory and acceptable with respect to intended use of the water. In the present chapter we deal with domestic water supply in which the nature of the treatment depends, not only on intended use, but also on the quality and condition of the source of supply, the *raw water*.

TREATMENT IN RELATION TO SOURCE AND QUALITY

Sources. The two principal sources of domestic water supply are surface waters and ground waters. As previously indicated, surface waters are exposed to the greater opportunity for pollution of the more undesirable sort. Even waters from so-called virgin sources are subject to surface wash during storms and to pollution, direct or indirect, resulting from the presence of campers, hunters, fishermen, and others on the watershed. All surface waters require treatment prior to distribution. The extent of required treatment may range from simple disinfection for the better-protected waters to most elaborate combinations of processes for the highly polluted river waters. Some ground waters that are well protected and that are derived from saturated soil and not from cavernous underground streams can be utilized with safety without treatment. There is always more or less uncertainty, however, concerning the actual underground condition and the past history of a ground water. Glacial drift, for example, is an ideal aquifer from the point of view of protection, but it may contain strata of large boulders which are the equivalent of the water-worn seams and caverns of a limestone formation. There are also possibilities of short circuits and leakage around well casings, of breaks in near-by sewers and other unfavorable conditions developing. Untreated ground waters should be subjected to careful bacteriological control, and the added safety factor of disinfection will generally be found justifiable.

QUALITY. The combination of principles to be used in the treatment of a particular water will depend also upon the nature, concentration, and state of the polluting material. These factors vary so widely from place to place that no standardized treatment system can be universally employed; a combination of principles must be adopted for treatment for each particular situation. Table 50 indicates combinations of principles frequently used in practical treatment systems for certain typical waters.

TABLE 50

TREATMENT OF WATER FOR DOMESTIC WATER SUPPLY

Combinations of Principles Employed According to Source and Quality of Raw Water

Source and Quality of Raw Water	Combination of Principles Employed in Treatment
Virgin surface waters	1. Disinfection
Surface waters of good quality	1. Coagulation 2. Hydraulic separation (sedimentation) 3. Mechanical (rapid-sand filtration) 4. Disinfection 5. Chemical (*p*H adjustment)
Surface waters of poor quality	1. Chemical (aeration or activated carbon) 2. Coagulation 3. Hydraulic separation (sedimentation) 4. Mechanical (rapid-sand filtration) or 5. Biological (slow-sand filtration) 6. Disinfection (pre- and post-) 7. Chemical (*p*H adjustment)
Ground waters of proved safety	No treatment
Ground waters subject to slight pollution, actual or potential	1. Disinfection
Hard waters — ground or surface	1. Chemical (softening) 2. Hydraulic separation (sedimentation) 3. Mechanical (rapid-sand filtration) 4. Disinfection

GENERAL CLASSIFICATION OF TREATMENT SYSTEMS. It is evident that there are many possible combinations of treatment principles, but systems, in general, can be classified, according to the filtration principle employed, into *slow-sand filtration and rapid-sand filtration.* Analyses of the systems will be made on the basis of principles employed, design (functional) of treatment units, operation, and efficiency.

SLOW-SAND FILTRATION

COMBINATION OF PRINCIPLES AND FLOW DIAGRAM

The slow-sand filtration system may be used to treat a surface water supply for a small community. This system generally employs two basic principles of treatment, biological and disinfection. The major operating units employed in the application of these principles are shown in the schematic flow diagram, Figure 89.

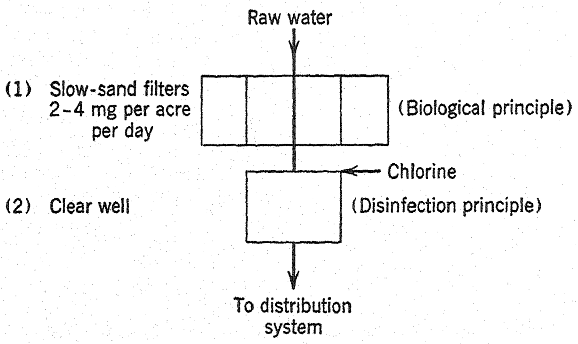

FIG. 89. Slow-sand filtration system flow diagram.

Raw water is taken directly from the stream or surface storage reservoir to the slow-sand filters to remove fine suspended matter, color colloids, and bacteria (biological principle). It then passes to a filtered water storage basin where it is chlorinated (disinfection principle). It is then ready for delivery to the distribution system.

FUNCTIONAL DESIGN AND UNITS

THE FILTER. The filter unit comprises a water-tight container with floors slightly ridged and sloped to receive a drainage system and (usually) roofed and with access manholes. A grid of 6- to 8-inch open-jointed tile laterals is laid on the floor, spaced on about 6-foot centers and draining to a central collection channel.

About 12 inches of graded gravel, ranging in size from 2 inches at the bottom to 1/16 inch at the top, is placed around and over the tile. On this *underdrain system* there is placed some 24 to 48 inches of graded filter sand with an effective size of 0.2 to 0.4 millimeter and a uniformity coefficient of 1.5 to 3.0.*

There is an interrelationship between size and depth of sand, rate of filtration and quality of raw water, which governs the selection of sand for any particular installation. Where high efficiencies are desired, the smaller size of graded sand with the larger bed depth is selected; where higher rates of filtration are desired, at somewhat less efficiency, the coarser more uniform sand and less bed depth are used.

Space from the top of the sand to the roof should be at least 6 feet, to provide headroom for workmen during cleaning operations. In severe climates, 2 to 4 feet of earth cover with a sod topping is usually placed on the roof to protect against freezing.

The filtered water collected in the underdrain system joins a piping system, provided with a *Venturi meter* to measure the discharge and suitable valves, usually manually operated, to regulate the flow from the filter unit. A gage is installed to measure the gradual *loss of head* through the filter as dirt accumulates on the sand bed. Raw water is admitted to the filter unit through a valved piping system entering above the level of the sand.

Regardless of size of the plant, at least four filter units should be provided, in order to maintain supply when one unit is out of operation for cleaning. In large plants the size and number of units are increased. However, an individual unit seldom exceeds one acre.

THE CLEAR WATER WELL. Either directly beneath the filter or at some other convenient location there is a concrete tank for storage of the filtered water. This is known as the *clear water well.* Its capacity will depend upon the excess capacity provided in filter units and the storage of filtered water provided at other locations in the system. If no excess filter capacity above the average daily demand is available, about 20 days of filtered supply must be provided in order to have sufficient water to cover excessive consumption during protracted periods of high demand. If filter capacity is greater than 130 per cent of the average daily demand, then filtered water storage may be reduced to about one day's supply.

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* The *effective size* of a sand aggregate is the size (in millimeters) than which 10 per cent of the sand (by weight) is finer. The *uniformity coefficient* is the size than which 60 per cent is finer divided by the effective size

CHLORINATION. In water treatment chlorination is the usual method of disinfection. The chlorination unit includes the special apparatus required to control and measure the rate of application of the chlorine (the *chlorinator*) together with suitable housing, pipe lines to convey the chlorine solution to the point of application, and other appurtenances. The design also includes storage to provide the necessary time of contact of the chlorine with the water prior to delivery to the distribution system.

The chlorination units are usually housed in a separate building or in a room separate from the remainder of the operating building, preferably with access from the exterior, and provided with adequate ventilation. The solution is piped to the entrance of the clear water well or, under suitable conditions, directly to the water as it enters the distribution system. This latter arrangement, however, is permissible only if there is sufficient contact time (at least 15 minutes) before the line is tapped for the first consumer. Precaution must likewise be taken to avoid the delivery at this tap of too high a residual of chlorine, which may be objectionable.

CHLORINATORS. The rapid growth of chlorination in the waterworks field, leading to its almost universal acceptance as a sole means of protection or as an adjunct to other treatments, has been due in large measure to the commercial introduction, about 1910, of the anhydrous gas compressed to liquid form, and the subsequent development of apparatus for applying the gas to water. Liquid chlorine is commonly provided in steel cylinders of 100 or 150 pounds capacity and in 1-ton containers.

Chlorinators operate upon two basic principles, control and measurement. Control involves the design and use of valves of suitable noncorrosive material and capable of fine and permanent adjustment. The pressure of the gas, as it evaporates from the liquid in the original container, varies with the liquid temperature, and a constant pressure is quite necessary in the operations of control and measurement. Hence, a primary requirement is a pressure-reducing valve which will accept the varying pressure on the tank side and deliver gas at a constant (reduced) pressure to the apparatus.

Measurement is accomplished by a variety of modifications of the basic principle of the orifice. This principle is illustrated in Figure 90*A*. The rate of flow of a gas through an orifice is proportional to the square root of the pressure drop as indicated on the manometer. A manometer scale is calibrated for each orifice, indicating the rate of flow in pounds of chlorine per day. The practicable range of rates for a given orifice is between five- and sevenfold. That is, according to the actual size of orifice employed, a machine, having a sevenfold range may be operated to feed from 10 to 70, 50 to 350 or 100 to 700 pounds of chlorine per day.

For rates of application between 0.25 and 10 pounds per day the volumetric chlorinator may be employed. One type of this device shown in Figure 90*B*, is merely a gas siphon. Chlorine enters from above at a controlled rate and under sufficient pressure to force the water downward and out of the siphon (inner) chamber. At the position illustrated the gas blows out the siphon tube, and the contents of the siphon chamber escape to the outer chamber and thence to the outlet of the apparatus. At the same time the water rises in the siphon chamber to its initial upper level. The amount of gas discharged per pulsation is determined at the factory, and the dose is regulated by adjustment of the control valve and counting the pulsations per minute.

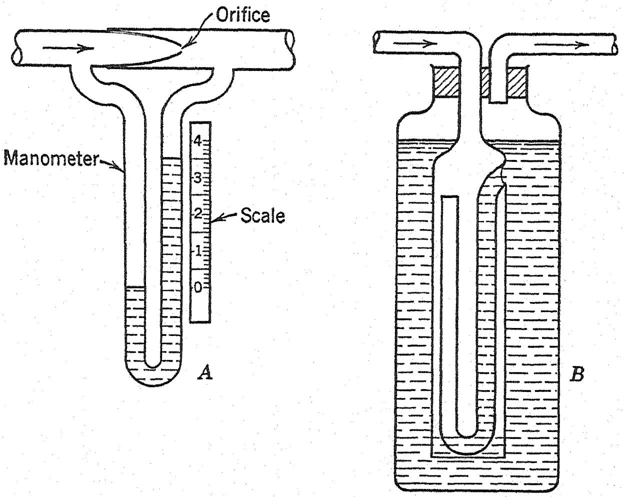

Fig. 90.

A The orifice principle. *B* Pulsometer.

For still smaller quantities the gas is merely permitted to bubble from a fine orifice, and the calibration chart gives the rate of flow corresponding to any given number of bubbles per minute.

Amplifications and improvements of the basic principles have led to the vacuum chlorinator, in which the measuring and control parts are all under a slight vacuum, (Figure 91), and are visible for inspection while the apparatus is in operation; the automatic chlorinator in which the rate of application, once set to supply a given concentration in parts per million, automatically keeps step with a varying rate of water flow in the main; and, recently, an electrode device which measures the residual chlorine in the treated water, and automatically adjusts the feed to maintain any desired residual, at the same time recording that residual on a chart.

HYPOCHLORITE FEEDERS. It is frequently convenient, in small installations, to employ a solution of hypochlorite as a source of chlorine. The small quantities of solution required and the nature of the solution make the use of orifices for control rather unsatisfactory although they may serve in emergency. Most of the hypochlorite feeders work on the principle of the diaphragm pump or of the displacement pump. Control is obtained both by adjustment of the length of the pump stroke and by varying the strength of the solution. The *hypochlorinators* or *reagent feeders* are available either as constant delivery or proportional feed devices.

OPERATION

MATURING. The slow-sand filter is basically a biological mechanism. Consequently, a new filter is not effective until the beds are matured. This may require 1 to 4 months, depending upon the water temperature (place and season) and the nature of the raw water. During this period a zoogleal coating develops on the sand grains. This growth is the actual biological agency responsible for the purification. Being aerobic it requires an adequate supply of dissolved oxygen in the water. Establishment of a matured bed will be evidenced by improvement in the quality of the effluent. The bed is then ready to be put into routine service.

THE NORMAL RUN. The filter is normally operated at a constant rate of 2 to 4 mgad.* The actual rate of operation for a particular installation will be dictated by design features, depth, size and grading of the sand, and others, and controlled by bacterial examinations of the effluent.

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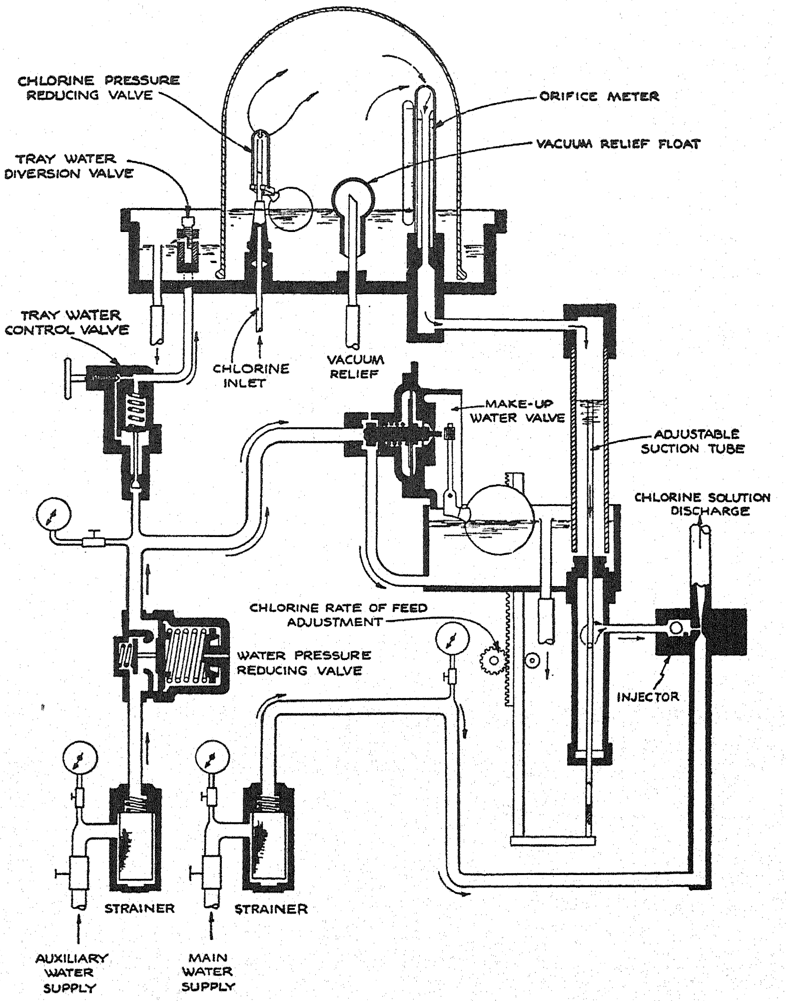
* Million gallons per acre per day, the unit in which filter rates are commonly expressed.



Courtesy of Wallace and Tiernan Co.

Fig. 91. Flow diagram for manual visible vacuum chlorinator-type MSV.

Water is admitted above the sand, usually by manual control of the inlet valve, with protection against overflow. In starting a filter run, the valve on the discharge line is partially closed in order to hold the discharge to the required rate. As the filter surface gradually becomes clogged with accumulated debris, the resistance to flow through the bed increases, and this increased resistance to flow must be compensated by a gradual opening of the discharge valve. The rate of flow is checked once or twice daily and the valves manipulated to maintain a uniform rate.

The resistance to flow through the bed is termed *loss of head* and is measured as the difference between level of water over the filter and that to which the water will rise in a vertical pipe connected to the discharge outlet. When the loss of head through the filter is equal to the depth of water above the sand, the bed should be cut out of service for cleaning. Operation of the bed under greater losses of head places the sand under negative pressure, which may cause air binding of the filter.

CLEANING. To clean a filter the inlet is closed, and the filter is allowed to drain to such a depth as will permit walking on the surface of the bed. Access is gained to the bed through manholes in the filter cover. About one inch of the top of the sand is scraped off, shoveled into an ejector which delivers the dirty sand to a washer, where the dirt is separated from the sand, leaving a clean sand for re-use. After a bed has lost about 6 inches of depth by several cleanings, new or washed sand is added to the top layer of the filter to reestablish proper sand depth. Frequency of cleaning will depend upon the suspended matter contained in the raw water. In general, it will range between 1 and 3 months. After cleaning, previously filtered water is admitted to the bed through the underdrain system until the level is a foot or more above the sand. This expels air from the sand and prevents scour, when the inlet valve is opened to admit raw water. The filter is first operated at a reduced rate, discharging to waste. The rate is gradually increased, until the bed is stabilized. The unit is then placed in full service and operated at a constant rate until the next cleaning.

DISINFECTION. The two major bases of control of disinfection are chlorine residual and bacteriological analysis. Because of the variation in chlorine demand and the variation in volume of water treated, the quantity of chlorine applied must be constantly adjusted to insure proper residuals of free chlorine for disinfection. Some designs provide automatic chlorinators which adjust for variations in volume of water treated and also for variations in chlorine demand. Other systems require frequent determination of residual and manual adjustment of the rate of chlorination.

It was seen (chapter 13) that many factors, such as *p*H, temperature, and time of contact, affect the efficiency of chlorination, and therefore the proper level of residual will vary with these factors and also depend on the design of the disinfection system and the nature of the water treated. In general, it has been customary to carry residuals, as determined by orthotolidine test after 10-minute contact periods; of 0.1 to 0.2 part per million. The recent trend is to increase this to 0.3 part or more, in order to retain a residual in the distribution system. Where chloramine (chlorine plus ammonia) is used, residuals of 0.3 to 0.5 are carried.

There are certain opportunities for misinterpretation of the results of the orthotolidine test especially in the presence of chloramines. An improved test, the orthotolidine arsenite (OTA) test* is more readily interpreted and gives more reliable indications as to the nature of the residuals observed.

Because of the complicated nature of disinfection by chlorination, reliance on chlorine residual alone is not adequate control. Although the bacteriological technique is much too involved and time-consuming to serve for daily routine control, bacteriological results do prescribe the level and limits at which routine chlorine residual control will insure proper disinfection. The day-to-day and hour-to-hour control of chlorination, then, will be carried out on the basis of residual determinations. The frequency of bacteriological tests will vary with the size of the plant, ranging from one sample a month for a population served of 2500 and under, to 300 samples per month for a population served of 1,000,000.

EFFICIENCY: ADVANTAGES AND LIMITATIONS

The major advantages of the slow-sand filter system are its ease of operation and the steady high efficiency which it is capable of maintaining. The filters are effective in removal of tastes and odors and are capable of producing, without chlorination, an effluent of uniformly good quality and a 99 per cent reduction in bacterial content. The added factor of safety of chlorination is usually con-

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* F. W. Gilcreas and F. J. Hallinan, *J. Am. Water Works Assoc.*, **36**, 1343, 1944.

sidered essential, however. The raw water does not receive preliminary conditioning before application to the filters and therefore does not require the highly skilled control necessary where coagulation treatments are involved.

On the other hand, slow-sand filters are definitely limited to the needs of small communities because of the area required. They are further limited to the treatment of waters which are relatively low in color and turbidity. If turbidity or color averages over 30 parts per million, or if the raw water is subject to periodic excessive turbidity concentrations from surface wash, the filters require frequent cleaning, an expensive and time-consuming process. Because of these limitations the slow-sand system has gradually given way to other methods of treatment.

RAPID-SAND FILTRATION

The rapid-sand filtration system has acquired its name by virtue of the high rates of filtration used in contrast to the earlier slow-sand filters. Rapid filters operate at 125 to 190 mgad (2 to 3 gallons per square foot per minute), some 60 times the slow-sand filter rates. Because of these high rates the filter beds are substantially smaller, but the system requires preliminary conditioning of the raw water before application to the filters, and frequent cleaning of the beds.

The rapid-sand filtration system is usually employed to supply the needs of large communities. It can successfully handle relatively highly polluted waters. It is a complicated process and usually employs, in various combinations, all of the basic principles of treatment.

COMBINATION OF PRINCIPLES AND FLOW DIAGRAM

The major operating units employed in the usual standard practice for the treatment of good quality surface waters are shown in the schematic flow diagram, Figure 92. Raw water is taken from storage reservoir or river, passed through rack screens (mechanical principle), thence to a flash mix and flocculators where a coagulant is added and flocculation is induced for the removal of color colloids and fine suspended turbidity (chemical coagulation principle). From the flocculators the water passes to sedimentation units where floc containing a large proportion of the color and turbidity is separated from the water (hydraulic separation principle). With this preliminary conditioning, the water is now ready for application to the rapid filters. Because of the high rate of operation and the frequent backwashing, the filters function primarily as a mechanical straining device, rather than as a biological bed, like the slow-sand filters. From the filters the water passes to a clear water well where it is chlorinated (disinfection principle), and, prior to discharge to the distribution system, the hydrogen ion concentration of the water is adjusted to reduce corrosiveness in the distribution system (chemical principle).

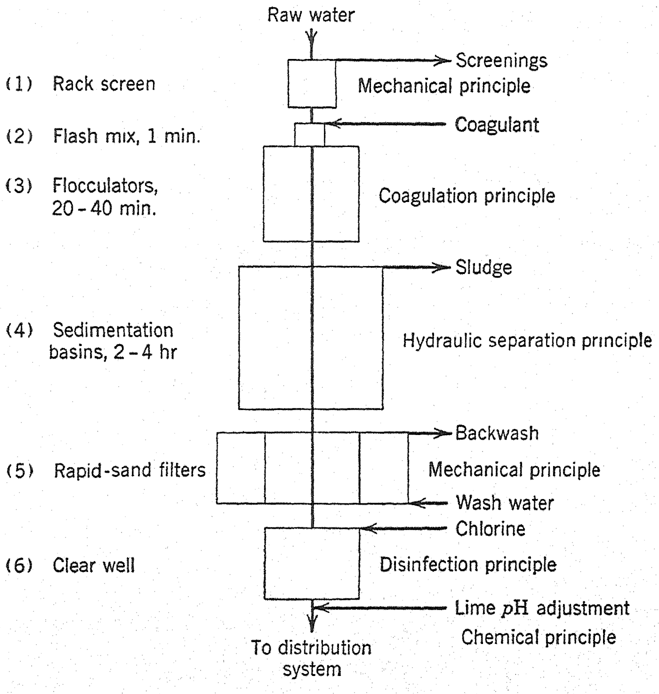


FIG. 92. Rapid-sand filtration system flow diagram.

FUNCTIONAL DESIGN AND UNITS

The *intake screens* comprise a simple rack of metal bars at about 3-inch spacing and are generally hand-cleaned.

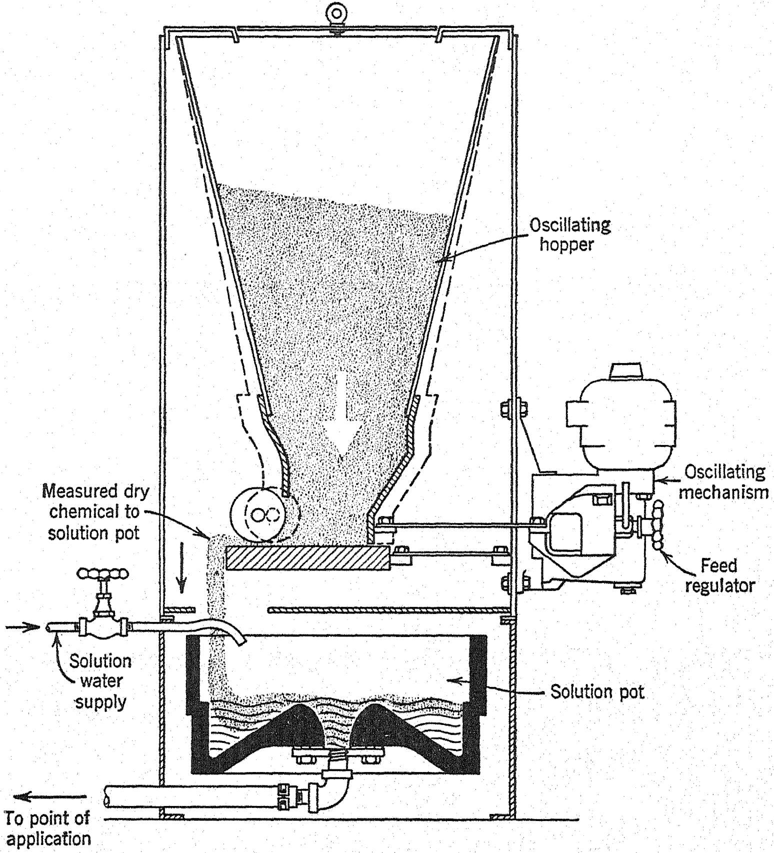
The *flash mix* is designed to provide a uniform distribution of coagulant to all portions of the water. This is provided in a separate chamber of about 1 minute detention, equipped with an agitation device. A separate flash mix can be dispensed with if a rapid mix is induced by some hydraulic means such as pumps.

CHEMICAL FEED. Addition of coagulants is controlled by chemical feed machines located in the central operating or chemical building, from which point the coagulant is piped to the flash mix. Chemical feed machines are of two types, solution and dry feed.

The *solution feed* type utilizes a hydraulic principle to regulate the discharge of definite volumes of dissolved coagulant of known concentration. The most common arrangement is a constant head tank equipped with an adjustable orifice calibrated for a range of discharge rates in proportion to water flow. The adjustment is manual or may be automatic by connecting a control device to the flow meter. Auxiliary to the feed device is a suitable coagulant dissolving box and a solution tank, for preparation of batches of coagulant of known concentration. The solution tank is connected to the feed device and is equipped with a gage for recording the volume which serves as an over-all check on the delivery rate of of the solution feed machine. Solution tanks and feeders must be provided in duplicate, and in large plants the feed requirements are divided among several machines with provision for emergency excess capacity in the event of breakdown.

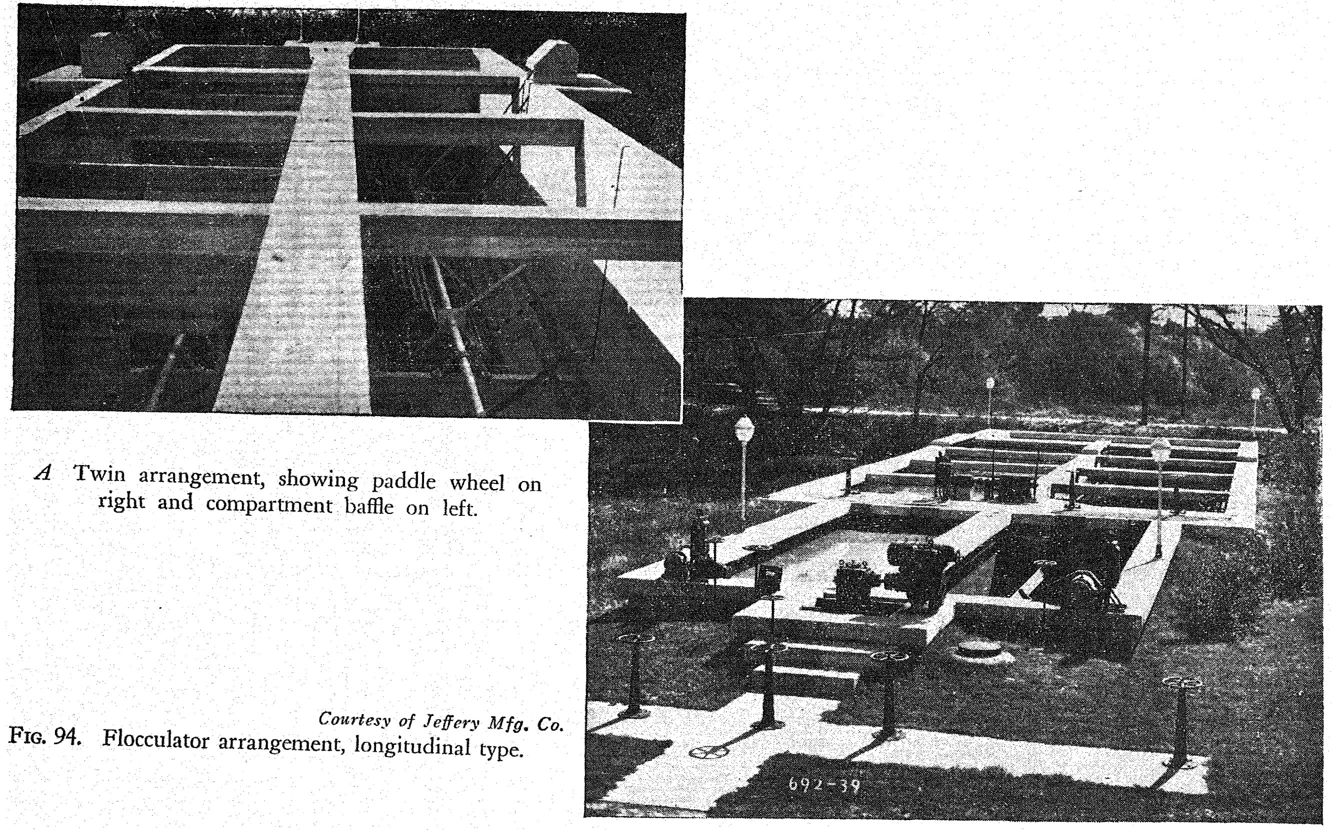
Dry feed machines are growing in favor over solution feeds, particularly in new installations. The chemicals are fed in granular or pulverized form as received from the manufacturer and do not require the preparation of stock solutions. In one design the feeders deliver a definite volume at regular intervals by an oscillating plunger which forces the dry chemical through an opening. The rate of feed can be adjusted by changing the size of the opening or the frequency of the oscillations. The chemical drops into a small solution pot into which water is admitted and is thus conveyed in a suitable conduit to the point of application. The dry feed machines are usually equipped with an overhead hopper, provided with an agitator to prevent caking (Figure 93).

Flocculating or conditioning chambers are usually rectangular in shape and are equipped with mechanical or hydraulic agitation devices to sweep the floc particles through the water. A type of



Courtesy of Wallace and Tiernan Co

Fig. 93. Chemical feed machine, dry-feed type.



A Twin arrangement, showing paddle wheel on right and compartment baffle on left.

B Twin arrangement, flocculators and sedimentation tanks.

Courtesy of Jeffery Mfg. Co.

FIG. 94. Flocculator arrangement, longitudinal type.

equipment used in flocculation is shown in Figure 94. Units are designed to provide a theoretical detention period of 20 to 40 minutes.

Sedimentation tanks are either circular or rectangular and are designed to provide a theoretical detention period of 2 to 4 hours. Some units are equipped with mechanical scraping devices to remove the settled sludge. Where sludge volumes are small, mechanical removal devices are omitted, and at infrequent intervals settling units are cut out of operation for cleaning. Care must be exercised in the design of the conduits connecting the flocculators to the sedimentation units to avoid breaking up the floc coming into the latter unit, thereby preventing good hydraulic separation.

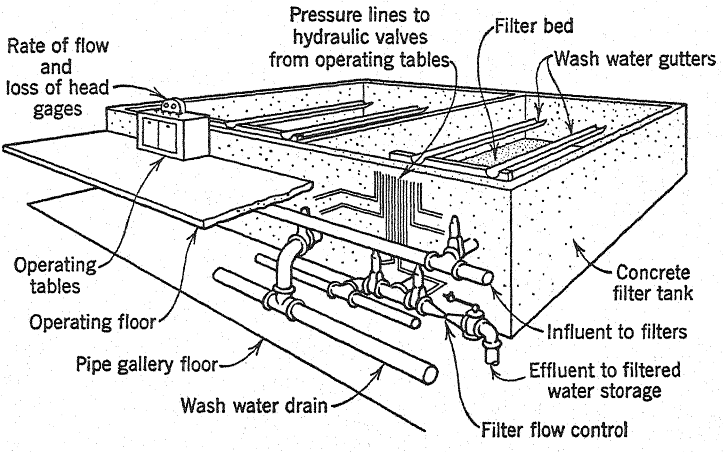


FIG. 95. Diagrammatic sketch of rapid-sand filter.

In earlier practice, coagulation and sedimentation were attempted simultaneously in a single unit without the aid of flocculators. Such installations provide a much longer detention time, ranging from 6 to 12 hours.

FILTERS. The rapid filters (see Figures 95 and 96) are constructed in units so arranged that all or a portion of the unit can be housed in a suitable filter gallery where filter operation can be seen and controlled by the attendant.* The filter unit comprises

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* The use of pressure filters (Figure 76, p. 420) is not recommended for municipal systems as the enclosing tank does not permit proper visual inspection during operation.

a reinforced-concrete water-tight container in which is placed an underdrain system for collecting the filtered water. This underdrain system also serves as the distributing device for backwashing the filter and must be carefully designed hydraulically to provide uniform distribution of backwash water to all portions of the bed.

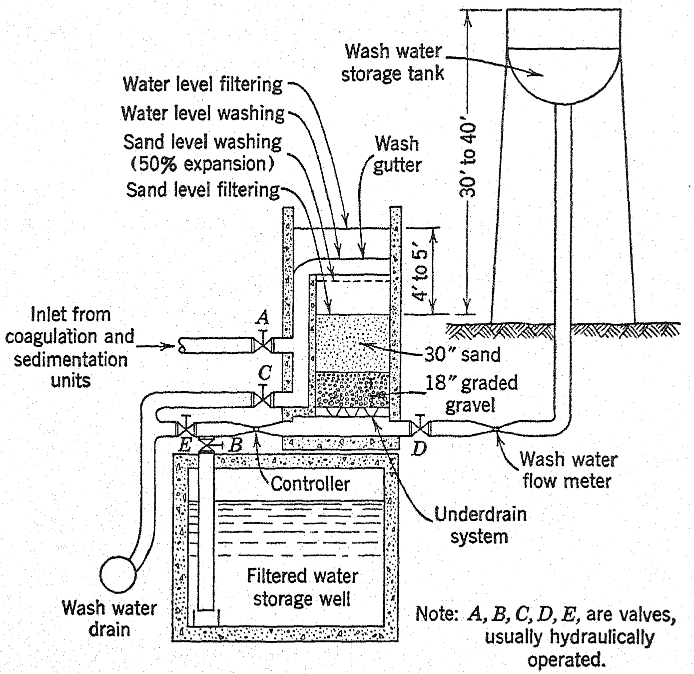

Fig. 96. Diagrammatic section of rapid-sand filter.

The Filtering Medium. On top of the underdrain system is placed about 18 inches of graded gravel ranging from 2 inch size at the bottom to 1/16 inch at the top (see Figure 96). On this is placed about 30 inches of special filter sand of rather uniform size and coarser than that used for slow-sand filters. The depth of the sand bed and the size of sand employed are closely interrelated and, in turn, are related to backwash rate requirements, length of filter runs between backwashes, and quality of filter effluent. The coarser the sand, the greater the depth and the higher the rate of backwashing necessary to clean the bed properly. Less frequent backwashing, however, will be necessary. There is a tendency among designing engineers at the present time to employ somewhat coarser material than has hitherto been the custom; sands of 0.6- to 1.0-millimeter effective size* being commonly specified. Each particular design will depend upon a careful evaluation of all the factors.

Wash-water gutters are spaced at intervals above the sand, extending across the filter width and discharging into a channel along one side. This channel and the gutters serve both as the outlet for backwash water and as the inlet for water during filtering.

The *walls of the filter unit* are carried sufficiently high to provide for 4 to 5 feet of water depth on top of the sand, plus an allowance for freeboard.

The *piping system* connected to the underdrain system of the filter units serves three major purposes: (1) to control the rate of discharge of the filtered water to the clear well; (2) to discharge the filtered water to waste, when necessary; and (3) to admit wash-water backflow to the underdrain during filter washing. An important feature of this system is the automatic flow-control valve which maintains a constant rate of filtration by automatically compensating for the increasing loss of head as the filter accumulates debris. The various valve arrangements are controlled from an operating table in the filter gallery adjacent each filter unit. Head loss and rate of flow gages are located on the same table.

The *clearwater well* is a water-tight structure, generally located beneath the filters and well protected from contamination by raw water. Its capacity is determined by the same principles as were discussed under slow-sand filtration (p. 503).

Filtered water is used as *washwater*. It is usually supplied from a *wash-water storage tank*, or in some small installations directly by wash-water pumps. Tanks should provide a volume sufficient to meet maximum needs for consecutive backwashing of at least two filter units. They should be 30 to 40 feet above the elevation of the sand bed, in order to insure adequate pressure. A Venturi or other meter is generally installed in the wash-water line to control and measure the rate of application of washwater.

The *chlorination units* are similar to those described for slow-sand filters. It is not unusual for additional units to be provided for prechlorination. Chlorine, applied with the coagulant, has a long

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* See p. 503 (footnote).

time of contact during passage through the flocculator and sedimentation tanks prior to filtration. The usual postchlorination is thus relieved of a considerable responsibility, and much more flexibility as to dosage is permitted in the first stage. Double chlorination is highly advantageous when high bacterial reductions are required or when taste and odor control is a primary objective. It is generally incorporated in the newer installations.

OPERATION

In contrast to the slow-sand filter, the rapid filter system requires constant skilled supervision both in the control of the preliminary treatment of the raw water and in the actual filtration. Successful operation of the entire system is dependent, primarily, upon proper conditioning of the raw water prior to filtration, that is, control of coagulation.

COAGULATION. In chapter 13 it was shown that there is no exact basis for predetermining the results of coagulation treatment. Control is based primarily upon small-scale laboratory jar tests (p. 459) to determine proper dose of coagulant with varying rates of flow and changing characteristics of the raw water. These bench tests are supplemented by frequent daily routine chemical analysis of raw and coagulated water. Since coagulation is very sensitive to variations in water characteristics, constant and careful control must be maintained to insure satisfactory results.

The practical objective of coagulation is to reduce both color and turbidity in the raw water to about 20 parts per million before applying it to the filters. Experience has demonstrated that filters will take this load and produce a filter effluent ranging from 0 to 5 parts. Consequently, for economical operation, the dose of coagulant applied is under constant adjustment to the threshold quantities required to maintain this quality of treatment. In the earlier practice it was thought desirable to allow a substantial quantity of floc from the coagulating operation to pass to the filters in order to accumulate a mat of floc on top of the sand to aid in the straining operation. This practice is successful in producing a filter effluent of good quality but necessitates more frequent filter washing, perhaps as often as two or three times a day.

The present tendency is to produce as complete separation of floc as possible with a minimum carry-over to the filters. With extreme care in the coagulation operations, excellent filter effluents are obtainable with filter washing intervals of 24 to 48 hours, a substantial economy in washwater as well as in coagulant.

The kind of coagulant used in treatment will depend upon the characteristics of the raw water. Alum is most commonly used and produces good removal of color and turbidity at *p*H ranging from 5 to 7.6. Color removal is more effective on the acid side, particularly with soft waters. For *p*H outside this range an iron coagulant is advantageous. Ferrous sulphate is effective for *p*H above 8.5. For highly colored acid waters, low in alkalinity and below *p*H 5 ferric sulphate can be used. Chlorinated copperas (chlorine and ferrous sulphate) can be employed, usually in the same *p*H range as alum. Although the iron floc has better subsidence characteristics, the possibility of having iron remain in solution because of improper control, particularly where ferrous sulphate is used, mitigates against its more general use, and, where feasible, preference is given to alum.

In the usual practice, variation in the factors affecting coagulation, such as *p*H, are compensated for by increasing the dose of coagulant applied. In special cases it may be more economical to adjust *p*H to the optimum point by addition of acid or alkali, and thereby reduce coagulant dose. Recently, attempts have been made to improve floc formation and save coagulant by the use of catalysts such as sodium silicate (p. 459).

The application of coagulants is controlled by the chemical feed devices previously described. Upon the basis of changing dosage requirements, as determined by the laboratory jar tests, the rate of application is adjusted, in proportion to the volume of raw water flow, either manually at frequent intervals during the day, or automatically. Feed devices must be checked frequently for accuracy of delivery, and must be maintained in good working condition. An adequate stock of chemicals should be stored to insure sufficient supply between deliveries from the manufacturer.

FILTRATION. BACKWASHING. Next to coagulation, the major operating problem is control of filtration. Good filter operation is primarily dependent upon proper washing of the filters. Filters are usually washed when the head loss through the filter has reached a predetermined point depending upon the design, usually 6 to 10 feet. As with slow-sand filters, this loss of head should not be carried to such an extent that it will produce negative head in the filter, which may cause air binding.

When the limit of head loss is reached, the operator closes the valve admitting the water to the filter and allows the water to recede to the level of the wash-water gutters. He then closes the valve on the discharge pipe from the filter and gradually opens the valve which admits water from a wash-water storage tank. The wash water enters the filter through the underdrain system throughout the entire unit and ascends vertically through the layer of graduated gravel, and then up through the sand bed itself, being discharged over the lips of the wash-water gutters and into the conduit from which it passes to waste.

The rate of backwash is gradually increased until the sand bed above the gravel is expanded about half its normal depth. In other words, if there are 30 inches of sand, the rate of backwash must be sufficient to expand the sand layer to 45 inches. This causes the sand to scrub itself relatively free of the finely suspended dirt which has been strained out of the water. The dirt is flushed over the edge of the wash-water gutter to waste. Care must be exercised, however, not greatly to exceed a 50 per cent expansion. Too high a rate of backwash will result in the loss of the finer sand and even the dislodgement of the smaller gravel in the underdrain system.

Backwashing is continued until the water above the sand is clear and free of dirt. Usually, 3 to 5 minutes of washing is sufficient to clean the bed. The wash-water valve is then closed, coagulated water from the sedimentation basin is admitted to the filter, and the unit is again placed in operation. The quantity of washwater used will range from less than 1 per cent to over 5 per cent of that filtered by the unit, depending upon frequency of washing.

The rate of application of wash water is expressed as inches of water rise per minute in the open area of the filter above the sand, or as gallons per minute per square foot of bed area.

1 gallon per minute per square foot = 1.6 inch rise per minute.

The limit of expansion of the sand is reached when the velocity of the water through the interstices of the sand grains equals or just exceeds the subsidence velocity of the sand grains in water. This subsidence velocity varies inversely with the viscosity of the water, which in turn increases with decreasing temperature. Hence the rate of backwash must be adjusted to compensate for water temperature. The relations are expressed by

$$R_T = R_{50} \times \frac{T + 10}{60}$$

where R_T = backwash rate at any temperature T
R_{50} = backwash rate at 50 degrees Fahrenheit which produces 50 per cent sand expansion

For sand sizes commonly used R_{50} is about 24 inches of vertical rise per minute. With a range in temperature from 40 degrees Fahrenheit in winter to 90 degrees in summer, the rate of wash in summer would be twice as great as that in winter, in order to produce the same sand expansion and, hence, the same cleaning. Failure to correct rates of backwash for temperature frequently results in poor filter operation.

As an aid to backwashing, some filters are equipped with revolving surface rakes or jets to break up the upper crust of the dirty bed before backwashing. These devices are particularly helpful where heavy loads are placed on the filter in the form of fine mud, or where old installations are so constructed that efficient backwash rates cannot be employed. Following a brief period of operation of the agitator, backwash is applied to flush out the material broken up. Savings in wash water and improvements in filter operation have been reported.

The so-called *air wash* is used in some installations as an aid to filter cleaning. Air, under low pressure, is admitted through the underdrain system or in a special air pipe system installed on the filter bottom. The air rises through the gravel and upon reaching the sand expands and agitates it. The level of the water in the filter is lowered below the wash-water gutters during air agitation, following which air is shut off and backwash applied to flush out the released dirt.

Insufficient backwashing often leads to a cementing of the sand and subsequent cracking of the surface so that only portions of it are properly expanded during washing. During normal filtering this condition leads to shortcircuiting and consequent serious loss in effectiveness. Another result of improper washing is the formation of "mud balls," small accumulations of dirt and organic matter, which may start at the size of a pea and which, when small, can be seen scooting on the surface of the expanded sand during backwashing. Mud balls will increase in size and accumulate in the lower depths of the sand bed where they interfere with normal filtration and prevent uniform sand expansion. When these conditions exist, the sand must be completely removed and cleaned or replaced, an expensive process.

EFFICIENCIES, ADVANTAGES AND LIMITATIONS

Bacterial. The rapid-sand filtration system, combining as it does the six basic principles of treatment, is a remarkably efficient process. From a bacterial standpoint it can successfully treat raw waters of an average coliform concentration of 5000 per 100 milliliters and produce a water of average concentration of 1 per 100 milliliters. This is an over-all efficiency of 99.98 per cent. Not only can the system maintain this efficiency, but also it can, under careful control, successfully handle occasional heavy overloads and provide a safe water of consistent quality.

Although the application of the disinfection principle is chiefly responsible for this high efficiency in treating highly polluted water, coagulation and filtration, nevertheless, play an important role, particularly in ironing out sudden overloads which may occur in a surface supply, such as the rush of surface wash following storms, or which may be associated with increase in concentration of pollution load during low runoff. Coagulation and particularly filtration take the peaks off these overloads and condition the water for final action by disinfection. An excellent evaluation of the efficiencies which can be practically developed in actual operation is afforded in a study made by the U. S. Public Health Service of treatment plants in the Ohio Valley and Great Lakes Basin.*

A general expression of the relationship between the bacterial quality of the effluent resulting from the treatment of water by various processes is

$$E = cR^n$$

in which E and R are the coliform concentrations in effluent and raw water, respectively, and c and n constants defining the characteristics of the operation. In most situations efficiency, expressed in terms of percentage removal, improves, but total residual numbers likewise increase with increased numbers in the raw water.

The demonstrated efficiencies of the plants operating in the Ohio and Great Lakes Basin are shown in Figure 97. These curves afford a guide as to what is practically obtainable by the use of various principles of treatment.

Physical. Unfortunately, the efficiency of coagulation and filtration in the removal of other objectionable characteristics of the

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* *U. S. Pub. Health Service, Pub. Health Bull.* 172, 1927; 193, 1930.

raw water, is neither so predictable nor constant. The primary responsibility for color and turbidity removal falls on coagulation, and unless coagulation is constantly adjusted to insure a uniform quality of water taken to the filters (not to exceed 15 to 20 parts per million), the filter effluent will reflect this poor preliminary treatment. Color and turbidity have only minor public health significance, but their presence in a domestic water supply in appreciable quantities is one of the chief sources of consumer complaint in a community accustomed to clear and colorless water. To meet a reasonable consumer demand the water, as delivered, should not exceed 5 parts per million in either color or turbidity.

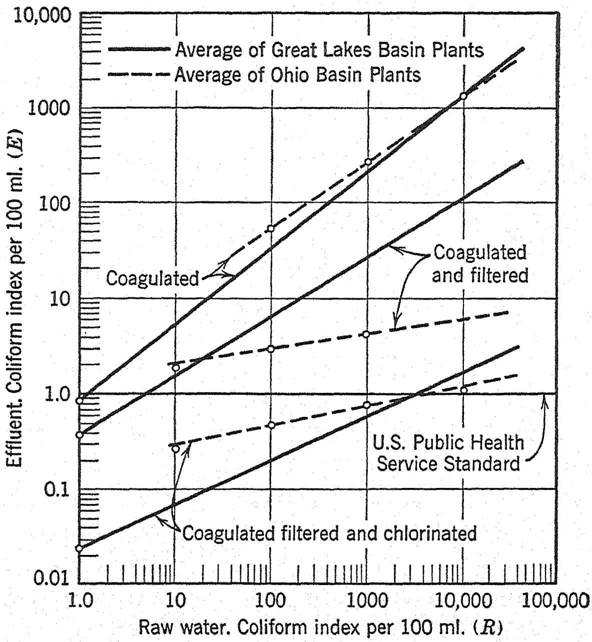


Fig. 97. Bacterial efficiency of rapid-sand filter plants in Ohio and Great Lakes basins.

(After U. S. Public Health Service)

Advantages and Disadvantages. The major advantage of the rapid-sand filter is its great flexibility in being able to produce satisfactory water under wide variations in the quality of the raw water. Also, the high rates of filtration reduce filter area to sizes economical for production of large quantities of water for large cities. Rapid filters require constant skilled supervision and are more complex in design and costly in operation. Nevertheless, the advantages inherent in the rapid filtration system have placed it in the dominant position in the field of water treatment.

MODIFICATIONS OF THE RAPID-SAND FILTRATION SYSTEM

Under certain circumstances it becomes necessary to treat raw waters which are so highly polluted that normal practice must be modified in one or another direction in order to produce an acceptable water. Four common types of excessive pollution, requiring such modifications, are:

Tastes and odors resulting from excessive microscopic growths or from industrial wastes.

Silt, associated with surface drainage from eroded land.

Excessively high concentrations of bacteria of direct sewage origin.

Heavy chemical pollution.

Heavy overloads may at times be carried in a standard system, with minor modifications, but they reduce the normal factors of safety, a condition not to be encouraged. The only solution may mean abandonment of old sources of supply and the development of new sources. Many communities throughout the United States must face abandonment of old sources which have gradually become more polluted because of failure to keep pace with pollution abatement control. Final decisions usually lag 10 to 20 years behind the need for change, from a purely technical point of view. Consequently, it is only through the ingenuity of the public health engineer in developing modifications of standard practice that these communities are protected while the decision is under debate. The problems arising are so varied that only a few of the successful practices will be outlined.

MODIFICATION IN TREATMENT FOR TASTE AND ODOR CONTROL

Where raw water of poor quality from the standpoint of taste and odor must be utilized as a source, three methods, all employing chemical principles, have proved successful. These are aeration, the addition of adsorptive media such as activated charcoal carbon, and superchlorination. These methods may be used singly or in combinations of two or all three.

AERATION. Where taste and odor are predominantly associated with a deficiency in dissolved oxygen or with dissolved gases such as hydrogen sulphide, aeration can be effectively employed (see p. 464). Aeration is usually applied to the raw water prior to coagulation, either by spraying the water through the air (through a nozzle or over a cascade), or by passing air, finely dispersed in small bubbles, through the water.

Cascades or nozzle sprays require a considerable head to insure intimate and sufficiently prolonged contact between the air and the water. If air is passed through the water, these head losses are not incurred, but air must be supplied (0.05 to 0.10 cubic foot per gallon of water) under low pressure and delivered through porous plates located at suitable depths (10 to 15 feet) in an aerating chamber. Air diffusers are more effective than cascade waterfalls, as more intimate contact is assured, but properly designed nozzle sprays are equally efficient.

ACTIVATED CARBON. Activated carbon is an efficient reagent for the removal of tastes and odors associated with industrial wastes, heavy sewage pollution, or excessive growths of micro-organisms. The carbon is usually applied to the raw water, simultaneously with the coagulant, by a dry feed machine. It is distributed with the raw water in the flash mix, and in the flocculating chamber it is deposited on the floc and swept through the water. It deposits in the sedimentation tank intimately mixed with the sludge. In the sludge, carbon is effective in controlling reintroduction of tastes and odors to the water passing over the deposited sludge. Some activated carbon passes through the sedimentation basin to the filters where it accumulates on or penetrates into the upper layers of the sand. This small carry-over affords further opportunity for adsorption of tastes and odors. The accumulation of carbon on the filter is flushed out in backwashing.

Activated carbon treatment is simple in application and extremely effective in eliminating a wide variety of tastes and odors. For ordinary conditions the required dosage is about 25 pounds per million gallons of water. The dosage is determined by trial in each instance. The employment of activated carbon is becoming routine in normal operation as an added factor of safety in assurance of water of high aesthetic quality.

Super- and Breakpoint Chlorination. Tastes and odors particularly those developing from the chlorination processes may frequently be dealt with by superchlorination or by breakpoint chlorination (p. 481). In superchlorination any required excess of chlorine may be applied, to be removed by subsequent treatment with a dechlorinating reagent such as sulphur dioxide, sodium thiosulphate, or sodium bisulphite.

MODIFICATIONS IN TREATMENT FOR HEAVY SILT

Excessive turbidity of raw water taken from silt-laden streams must be reduced by modification in preliminary treatment prior to application to the filters. Two methods of modifying the usual coagulation practice are commonly employed: preliminary sedimentation prior to coagulation or double coagulation.

Preliminary Sedimentation. If the suspended matter is of a character which can be removed by the principle of hydraulic separation with reasonable detention periods, preliminary sedimentation affords the simplest and most economical method of reduction in turbidity. If natural storage space is available, a relatively long preliminary sedimentation period can be provided in an impounding reservoir which can be desilted by dredging; otherwise, sedimentation tanks of 1 to 2 hours detention period, with sludge removal mechanisms, must be installed.

Double Coagulation. Very fine suspended matter does not respond to hydraulic separation, and special coagulation treatment must be resorted to, either by providing excess parallel coagulation and sedimentation capacity or by providing for series treatment. Series treatment involves reduction of a portion of the turbidity in a preliminary coagulation and sedimentation operation, the effluent of which is subjected to secondary coagulation and sedimentation to reduce the load to a level which can be handled by the filters without too frequent backwashing or other operational difficulties. Depending upon the silt load, a combination of preliminary sedimentation and double coagulation may be economically practiced.

MODIFICATIONS IN TREATMENT FOR EXCESSIVE BACTERIAL POLLUTION

Many communities are obliged to treat a raw water which exceeds the recommended limit of 5000 coliforms per 100 milliliters and are doing so with satisfactory results as measured by coliform standards. This is usually accomplished by heavy disinfection or by double filtration or by both. In borderline cases, prechlorination followed by postchlorination without superchlorination may be adequate. Prechlorination is applied with the coagulant, thereby providing a contact time equal to the detention period in flocculators and sedimentation basins. The dose is limited to that which gives a slight residual in the water taken to the filters. Postchlorination is applied to the filtered water, preferably as it enters the clear well to take advantage of the longer contact time. If pre- and postchlorination are not sufficient to reduce bacterial content, superchlorination may be employed.

Another modification to meet high bacterial loads is double filtration, with pre- and postchlorination. In double filtration usually all or a part of the effluent of the rapid-sand filters is applied to slow-sand filters as a finishing process. The slow filters may be designed to operate at rates higher than those usually employed. Because of the biological characteristics of the slow-sand filters, they serve as a dependable leveling device to reduce peak variations in bacterial load to levels that can safely be entrusted to chlorination.

Storage prior to treatment is also an effective means of leveling peaks and reducing bacterial concentration, simply by providing the time factor for normal death rate (see p. 401).

MODIFICATIONS IN TREATMENT FOR HARDNESS

Certain surface waters and many ground waters carry concentrations of dissolved inorganic compounds which are objectionable for primary water use. Foremost among these are the salts of calcium and magnesium, the major causes of *hardness* in a water. Salts of iron and manganese are likewise hardness (soap precipitating) constituents, but their effects in staining the hand bowl and discoloring the laundry are so much more objectionable that they are not commonly treated as hardness.

Calcium and Magnesium Hardness. Hardness of water for primary community use is not seriously objectionable unless it is excessive. From an economic point of view, however, saving in the family soap bill, central softening treatment of the entire supply before delivery to the consumer is definitely justified, where hardness exceeds 150 parts per million.

Soap is a poor softening agent. It is expensive, and the calcium and magnesium soaps that are formed are the familiar sticky curd which adheres to basins and fabrics in washing and laundry operations. The advantages of central softening of community water supply are coming to be more fully appreciated by the consumer, and many treatment plants in the hard water belts are being modified to include softening.

The particular process of chemical treatment to be employed in any specific instance will depend upon the character of the hardness (carbonates, sulphates, chlorides or nitrates of calcium and magnesium), their respective concentrations, and the degree of removal desired. We shall deal here with the general features of softening practice applicable to community supply and regarded as a modification of normal rapid-sand filtration system.

In general, modifications involve the substitution of chemical precipitation for chemical coagulation. However, where color removal as well as softening is involved, chemical coagulation and chemical precipitation can be carried on simultaneously in the mixing and flocculating basins. The large quantities of chemicals employed and the consequent great volume of precipitated sludge produced in softening requires modification in chemical storage and handling facilities as well as special means for sludge handling and disposal.

Four arrangements commonly employed in recent practice use, respectively, lime–soda ash, excess lime–recarbonation, lime–returned sludge, and lime and zeolite.

SOFTENING BY LIME AND SODA ASH

The lime–soda-ash process (Figure 98) is effective where both carbonate and sulphate hardness are to be removed, and where it is not necessary to reduce hardness below 75 parts per million.

Functional Design. Lime and soda ash replace the usual coagulant with but minor alterations in the rapid-sand filtration system. The flocculation chamber in which chemical coagulation is practiced is replaced by a tank of somewhat longer detention period (40 to 60 minutes), equipped with similar mixing devices to induce intimate contact of the chemicals with the water and to stimulate precipitation. Additional sedimentation capacity is desirable (3 to 4 hours), in units which can be operated in series or in parallel, for flexibility, and equipped with continuous sludge removal devices to handle the large volume of calcium carbonate sludge produced.

Disposal of this sludge is a major problem. It may be discharged directly to a watercourse, with due consideration of adequacy of runoff for dilution, effect upon fish life, formation of sludge banks, or discoloration of the water. It may be lagooned, but extensive areas are required. More expensive means for dewatering and drying, such as vacuum filters, or burning, with recovery of the lime for re-use, may be employed.

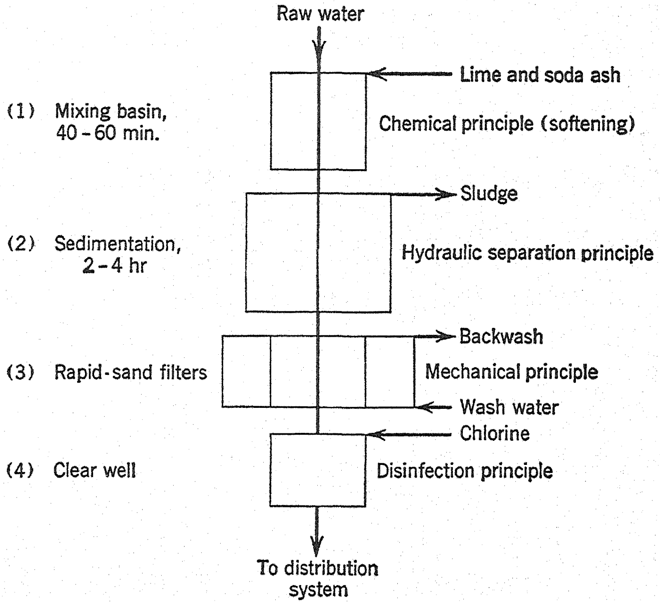


Fig. 98. Water-treatment flow diagram involving *lime–soda-ash softening.*

Operation. As with design, certain modifications in operation are essential. The required dosage of reagents, lime and soda ash, is determined by the mineral constituents in the raw water and can be predetermined from the reaction equations (see p. 466). It must be constantly adjusted to variations in volume, as well as to changing characteristics of the chemical constituents of the raw water.

Difficulties may be experienced in filter operation from a carry-over of very fine particles and also from the deposit of nonstable carbonate on the sand grains. Depending upon the *p*H, the treated water may be supersaturated with calcium carbonate, and contact with the sand grains then induces precipitation of a sticky carbonaceous coating on the sand which is not readily removed by backwashing. The sand grains gradually increase in size until masses of the upper layers are cemented together, seriously impairing filter operation. These formations can be broken up to some extent by putting the filter out of operation and spading the bed two or three times a year. Ultimately, however, it is necessary to replace the sand.

APPLICABILITY. In practical operation, the lime–soda-ash process can economically reduce hardness to 75 to 100 parts per million with a minimum modification in the normal rapid-sand filtration system. Where magnesium compounds form a substantial portion of the hardness, only limited softening can be obtained because of the formation of complex basic magnesium carbonates which remain in solution. The removal of these must be sought by other softening methods.

SOFTENING BY EXCESS LIME AND RECARBONATION

Where hardness is predominantly carbonate, including substantial quantities of magnesium carbonate, the excess lime–recarbonation process is generally effective.

FUNCTIONAL DESIGN. As is shown in the flow diagram, Figure 99, this process requires considerable modification in preliminary treatment units prior to filtration. Both mixing and sedimentation capacity must be increased and arranged to provide for series operation so that double mixing and double sedimentation can be practiced. A means for recarbonation must be provided, usually a combustion unit, furnishing carbon dioxide flue gas and reaction chambers. The chamber is 10 feet deep or more, and the gas is delivered and distributed through perforated pipes. Two such chambers are usually installed, one unit preceding the second mixing and sedimentation operation; the other preceding the filters. The remaining units of the treatment system are as in normal rapid-sand layout.

OPERATION. Since successful results in the excess lime–recarbonation process depend upon reactions at critical *p*H, control of operation requires continuous skilled supervision. Magnesium hydroxide is precipitated most satisfactorily at *p*H 10.6, where it is least soluble, whereas calcium carbonate at ordinary operating temperatures is least soluble at 9.4. This system of softening takes advantage of these characteristics in providing a split treatment, wherein magnesium is precipitated by the first mixing and sedimentation operation, through the application of lime, sufficient to produce a *p*H of 10.6. Following the separation of the magnesium hydroxide precipitate,

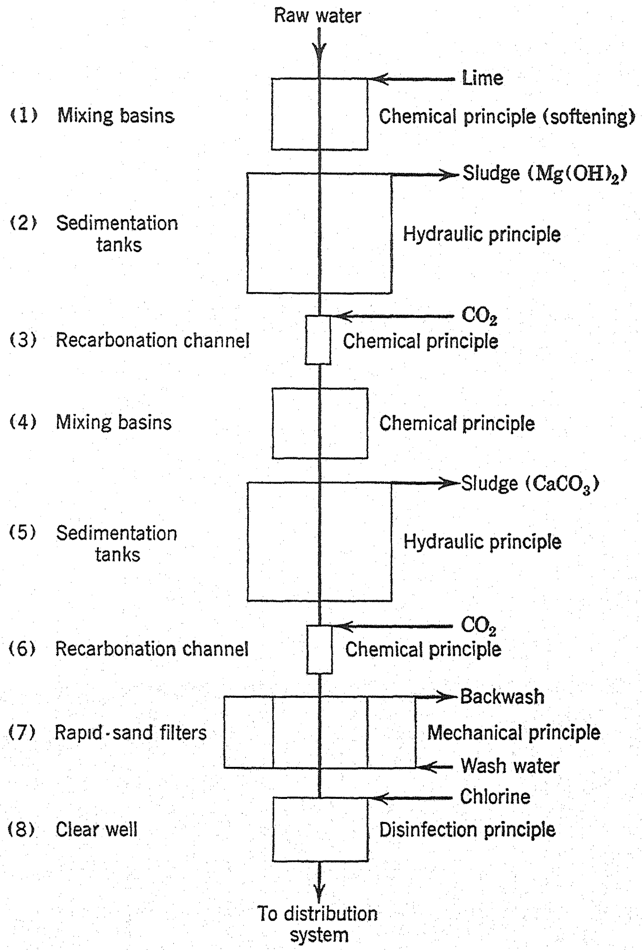


FIG. 99. Water-treatment flow diagram involving *excess-lime–recarbonation softening*.

the hydrogen ion concentration is increased by recarbonation to *p*H 9.4. With a second mixing and sedimentation operation, calcium carbonate is removed. In order to avoid the difficulties of filter operation associated with the lime-soda-ash process, the water is then further recarbonated, increasing the hydrogen ion concentration to about *p*H 8.7, sufficient to hold any remaining carbonate in solution. Sludge disposal with this system is similar to that practiced with the lime-soda-ash process.

Applicability. The excess lime process is more complicated and involves more operating units than the lime-soda process but it is capable of producing a water with as little as 30 to 40 parts per million of hardness. The recarbonization feature, in addition to aiding in hardness removal, protects the filtration units and the mains from incrustation by unstable carbonate, a phenomenon frequently experienced where softening is practiced.

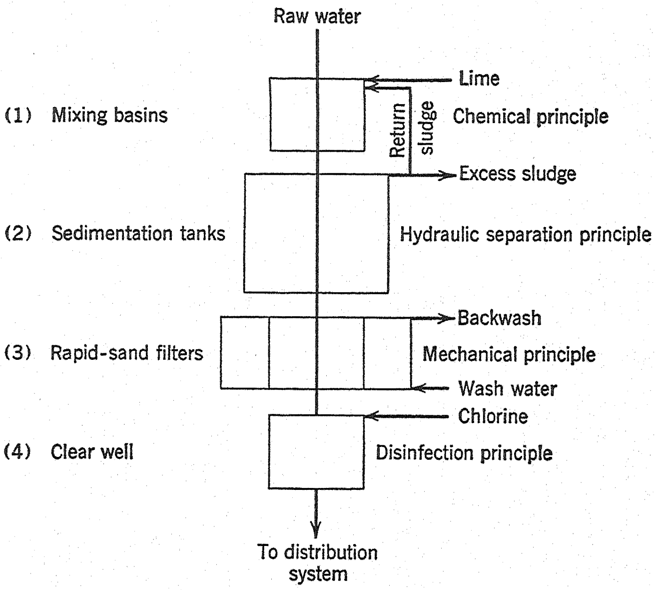
In the recarbonation practice, however, *p*H adjustment must take into consideration variations in calcium carbonate saturation as defined by the Langelier equation (p. 295), or an aggressive water may result. Current practice favors maintaining a positive Langelier index and controlling the unstable carbonate by sequestration with hexametaphosphate (p. 541).

SOFTENING WITH LIME AND RETURNED SLUDGE

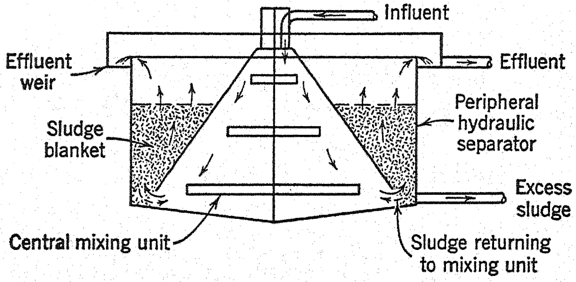
One of the difficulties in softening operations is the slow formation and subsequent sedimentation of precipitates. It has long been known that contact with previously formed precipitates accelerates the new formation by providing a nucleus upon which the finely divided newly formed material can deposit. Recent developments in softening practice have modified mixing and sedimentation operations by returning sludge, together with softening chemicals, to the mixing basin. The increase in precipitation thus induced minimizes subsequent deposits from unstable carbonates to such an extent that recarbonation is not essential prior to filtration.

Functional Design. As shown in the flow diagram, Figure 100*A*, this simplification in softening procedure does not greatly modify the normal rapid filter system, as chemical precipitation simply replaces the usual coagulation units. Special facilities must be provided, however, for handling sludge, including pumps to return settled sludge from the sedimentation unit to the mixing basin.

There are available, also, units which serve as a combined mixing and sedimentation basin,* wherein the return of sludge to the



A Water-treatment flow diagram involving *lime–return-sludge softening.*



B Sectional view of combination mixer and hydraulic separator (to replace units (1) and (2) above).

FIG. 100

mixing unit is automatic, shown, in principle, in the sectional view, Figure 100*B*. The mixing unit is contained in the central portion of

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* "Precipitator" and "Accelerator."

the basin, surrounded by an upward-flowing hydraulic-separation unit, in which the water passes vertically upward through an accumulated blanket of precipitate. Clarified water is discharged over surface weirs. A portion of the accumulated blanket of precipitate which is retained in the hydraulic separator automatically settles back into the mixing unit, and the excess accumulation is withdrawn to disposal. Intimate contact of newly-formed precipitate with the previously settled sludge is effected first in the mixing unit, and again in its vertical passage through the accumulated blanket in the hydraulic separator. A substantial reduction in sedimentation time is possible in such a combination unit (reduction from 3 or 4 hours to 1 or 2 hours).

OPERATION. In addition to the usual care in operating control, where return of sludge is practiced, consideration must be given to the proper concentration of sludge to be maintained in the mixing unit and the prevention of the passage of nonsettling sludge to the filters. To insure such separation, it may be necessary to introduce a coagulent such as alum, together with the chemical softening agents to remove fine precipitate by coagulation.

Utilization of return sludge permits a substantial reduction in capacity of softening units and saves on chemicals required, and, at the same time, hardness can be reduced to 30 or 40 parts per million.

LIME AND ZEOLITE SOFTENING

If a high degree of softening is desired or if difficulties are experienced in removal by precipitation methods, a split treatment, utilizing lime and zeolite softeners, may prove economical.

FUNTIONAL DESIGN. A typical flow diagram for such split treatment is shown in Figure 101. The layout may comprise the usual excess lime–recarbonation units or lime–returned sludge facilities, with or without simultaneous coagulation, as preliminary treatment to applications to rapid filters. After the filters, part or all of the effluent is passed through the zeolite softeners (p. 467) to reduce hardness further to desired levels.

Zeolite softeners are similar in construction to the rapid-sand filter. About 24 to 48 inches of zeolite sand are placed on an underdrain system, arranged with inlet and outlet controls similar to those of a filter to regulate the rate of filtration and to permit backwashing and the introduction of salt brine for regeneration. Auxiliary to the bed is a salt brine solution and storage tank.

OPERATION. In addition to the usual softening control prior to sand filtration, it is essential that turbidity and unstable carbonates are not introduced into the zeolite bed, where they will accumulate in the zeolite sand and clog the softener.

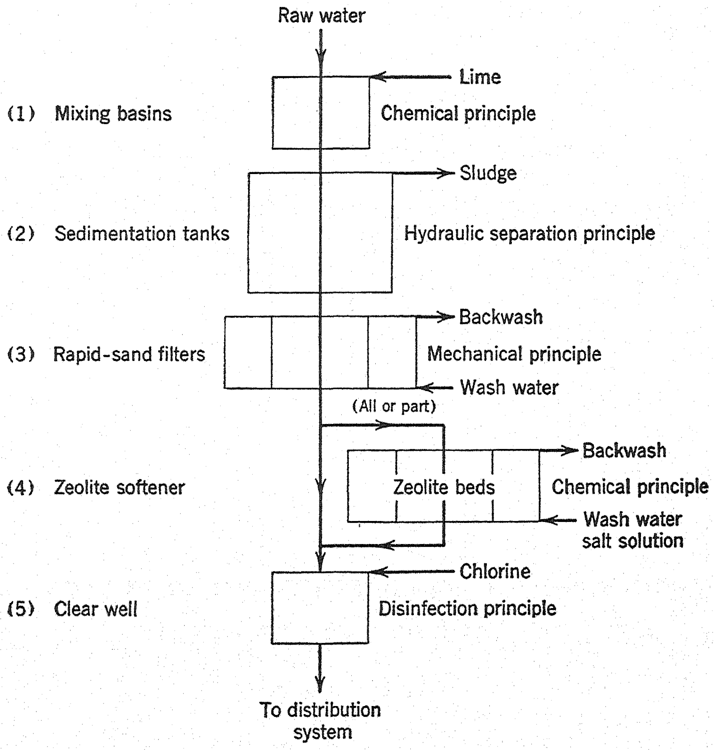

FIG. 101. Water-treatment flow diagram involving *lime–zeolite softening.*

As the zeolite exchanger accumulates the calcium and magnesium hardness, its efficiency drops to a point where it must be regenerated. The bed is cut out of operation and given a short period of backwash, usually at a much lower rate than that practiced in sand filtration. Followng this, a sodium chloride solution (5 to 10 per cent) is applied through the underdrains and allowed to remain in contact with the zeolite for a period of 5 to 15 minutes, while sodium is exchanged for the calcium and magnesium. The brine solution is then backwashed from the bed, and the unit is again ready for normal softening operation.

This system of split treatment of lime and zeolite softening is particularly effective where the carbonate portion of hardness is removed by lime precipitation, and the sulphate hardness is left for removal by the zeolite bed. Any degree of softening desired can be obtained, depending upon the proportion of the water which is passed through the zeolite unit.

MODIFICATIONS IN TREATMENT FOR IRON AND MANGANESE

A second group of compounds often requiring special treatment for removal includes iron and manganese. Whereas hardness in a drinking water is not seriously objectionable unless excessive (100 parts per million or over), iron and manganese are undesirable even in such low concentrations as 0.3 part per million. Their complete removal is sought wherever feasible.

Several types of treatment are available. The particular process to be employed will depend primarily upon the source of the water and the nature of the compounds of iron or manganese present. Surface waters may contain iron and manganese as soluble complex organic compounds, whereas ground waters, high in CO_2 content, may hold substantial quantities in solution as bicarbonates or complex hydroxides. Although iron and manganese are usually classed together, iron is removed more readily than manganese, and therefore their relative concentrations influence the treatment employed.

Frequently hardness as well as iron and manganese are involved, and the processes employed in softening, including the synthetic zeolites, are also effective in the removal of iron and manganese. In general, where softening is not employed, removal of iron and manganese is effected as a modification of the rapid-sand filtration system, usually by substituting one or more chemical principles (oxidation, *p*H adjustment, contact adsorption) for coagulation, or by applying both chemical principles and coagulation.* Three

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* Where the concentration of iron and manganese is low and only at times troublesome, the expense of a special treatment system for removal may not be warranted. In such instances, the sequestration of iron and manganese by simple application of hexametaphosphate will afford an economical control and protection against iron and manganese staining (p. 541).

arrangements commonly employed in conjunction with rapid-sand filtration, as indicated in Table 51, are shown in flow diagrams, Figures 102, 103, and 104.

TABLE 51

MODIFICATION OF TREATMENT OF WATER SUPPLY FOR IRON AND MANGANESE REMOVAL

Source and Nature of Raw Water	Character of Iron or Manganese Present	Treatment Modification preceding Rapid Filters
1. Ground waters of moderate hardness, not requiring softening and free of color and turbidity	Ferrous iron, practically no manganese	Aeration (flow diagram, Figure 102)
2. Ground waters of moderate hardness, not requiring softening and free of color and turbidity	Ferrous iron and manganese	Aeration and contact adsorption (flow diagram, Figure 103)
3. Surface or ground waters containing color and turbidity	Organic iron and manganese	Oxidation and coagulation (flow diagram, Figure 104)

IRON REMOVAL BY AERATION

Ferrous iron (not organic in character) held in solution by high CO_2 content can readily be removed by aeration (flow diagram, Figure 102). If the raw water is practically free of color and turbidity and manganese is absent, the usual coagulation operations are not necessary, and preliminary treatment prior to filtration consists simply of aeration and sedimentation. Aeration serves the dual function of supplying oxygen for oxidation of highly soluble ferrous to less soluble ferric iron and by reducing CO_2 to about 5 parts per million.

Aeration can be applied either by passing the water in a fine sheet or spray through the air, or by bubbling air through the water. Air diffusion in a chamber of 15 to 20 minutes detention is preferable, since this also serves as a mixing unit in which more complete precipitation is induced and a more readily settleable floc produced.

Following aeration, the water passes to a sedimentation unit of the usual type wherein the iron floc [$Fe(OH)_3$] is removed by hydraulic separation. Any fine iron floc remaining is removed by the rapid-sand filters. Control is simple, as no chemicals or coagulants are applied.

IRON AND MANGANESE REMOVAL BY AERATION AND CONTACT ADSORPTION

When both iron and manganese are present as inorganic compounds and the water is relatively free of color and turbidity, aeration, augmented by contact adsorption, is effective in their removal. Manganese is not readily precipitated by oxidation. It tends to form colloidal hydroxide or complex hydrated oxide suspensions, not removable by subsequent sedimentation. Separation is effected in the so-called *contact aerator* by physical adsorption through intimate contact with previously deposited material.

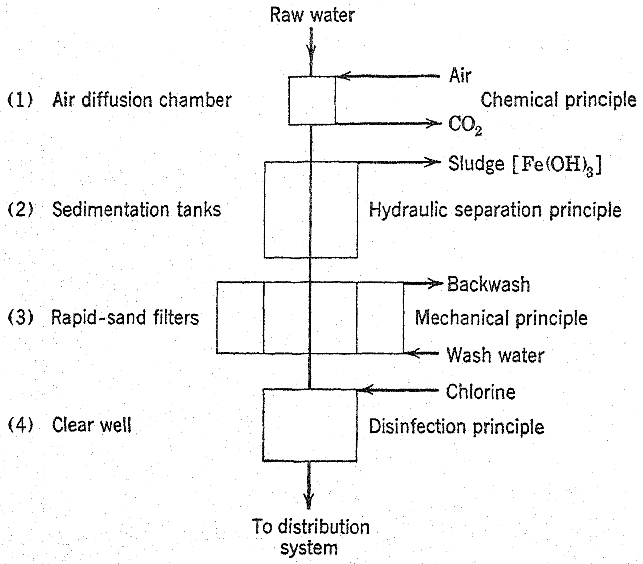

FIG. 102. Water-treatment flow diagram involving *iron removal by aeration.*

A contact adsorption unit is similar to a filter. It has an underdrain system and 2 or 3 feet of medium, such as coke, crushed stone, gravel, coal, or manganese ore. In earlier practice it was thought necessary to provide aeration by arranging the contact medium in a series of shallow trays separated by air spaces. Such an arrangement involves substantially greater head loss and is no more effective than the single unit, providing the water itself is well aerated. The unit is usually operated as a submerged upward-flow bed.

Means for freeing the bed of excess accumulation of deposit are provided either by backwashing facilities or by spray jets laid within the bed. Routine cleaning, once or twice a day, is accomplished by a sudden opening of the control valve increasing the flow and producing a flushing action. Backwashing or jet washing is resorted to weekly or so, depending upon the rate of accumulation.

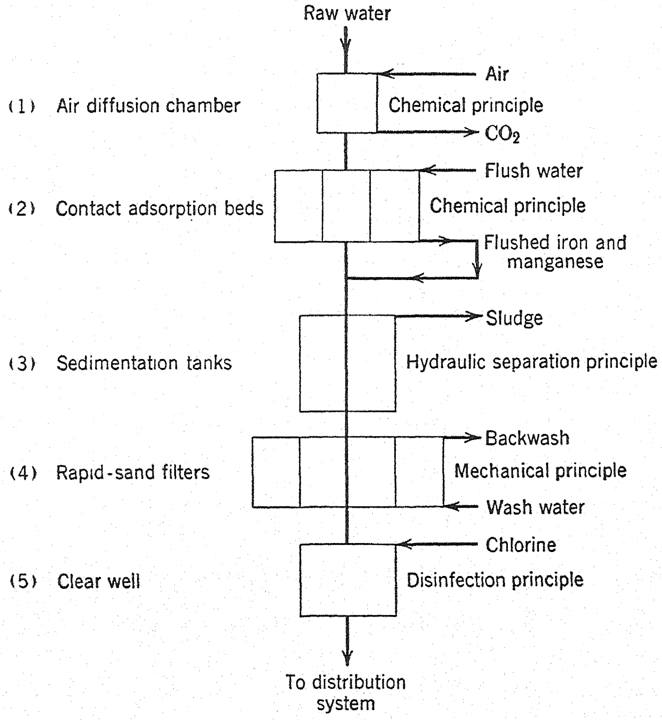

FIG. 103. Water-treatment flow diagram involving *iron and manganese removal by aeration and contact adsorption.*

Sedimentation tanks of the usual design remove most of the precipitated material passing or flushed from the contact unit. Some finely suspended matter, usually iron, passes through these tanks and is strained out in the filter which follows. Manganese not precipitated in the contact unit is deposited in the lower levels of the filter, the sand, becoming coated and acting as a further contact medium.

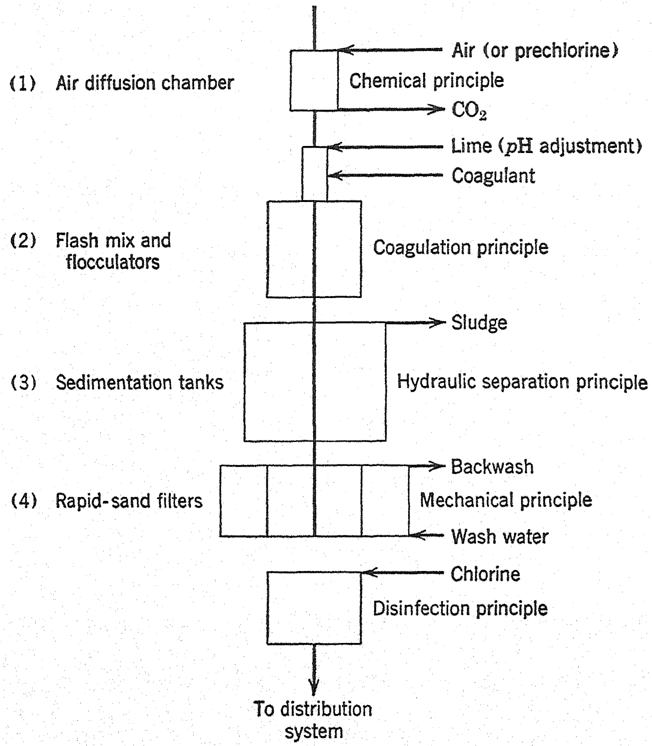

FIG. 104. Water-treatment flow diagram involving *organic iron and manganese removal by oxidation and coagulation.*

The system does not reach maximum efficiency until the media have become coated with precipitated manganese. Prechlorination is an aid to oxidation and is also effective in preventing the growth of the iron bacteria, *crenothrix*. Operating control is simplified to the extent that coagulation operations are eliminated. It involves supervision of the contact units and filters with analytical check upon the effectiveness of iron and manganese removal.

IRON AND MANGANESE (ORGANIC) REMOVAL BY OXIDATION AND COAGULATION

When iron and manganese are present as complex organic compounds in waters also carrying color and turbidity, oxidation by aeration or prechlorination and coagulation offer an effective treatment. Very little modification in the standard rapid filter is necessary other than to provide for air diffusion and insure maximum flexibility for operation of the various units, particularly for series or parallel coagulation, and ample chemical feed equipment. The problem is primarily one of operating control to keep in step with varying characteristics of water and of changing nature of iron and manganese content.

Coagulation plays the major role, as organic iron and manganese compounds are predominantly colloidal. Oxidation and *p*H adjustment to alkaline reaction (between *p*H 8.5 and *p*H 9.5) insure formation of least soluble end compounds. Coagulation at this reaction is best accomplished with ferric chloride or ferric sulphate. At times, however, alum coagulant may be used without *p*H adjustment and satisfactory removal effected. Constant skilled control is essential, and the particular coagulant employed will be governed by economy in use of chemicals as well as effectiveness in removal of iron and manganese.

SODIUM HEXAMETAPHOSPHATE

A recent development in the control of corrosion of metals by water and the prevention of excessive incrustation of pipes and plumbing is *sodium hexametaphosphate*. The soluble meta- and pyrophosphates possess characteristics which are capable of sequestering or taking up in water such ions as calcium, magnesium, iron, and manganese, and of holding them in solution, thus preventing their precipitation by heat or by reaction with other substances. Another property of metaphosphates is their ability to form films on surfaces of metals and on nuclei of precipitates. The films on surfaces of metals serve as protective coatings, inhibiting corrosion and tuberculation; the coatings on nuclei prevent agglomeration and precipitation, inhibiting incrustation of distribution mains and household plumbing.

Frequently, well waters contain small quantities of iron in solution which produce "red water" troubles. The addition of metaphosphate in a ratio of 2 parts per million for each part per million of dissolved iron is sufficient to sequester the iron and hold it in solution, even when the water is later aerated, chlorinated, or heated. Dissolved manganese can be similarly controlled.

Hard waters, high in bicarbonates can be stabilized by the addition of 1 to 2 parts per million of metaphosphate. Ordinarily, such waters result in heavy scale formations with loss of CO_2 or with increase in temperature. The metaphosphate prevents the precipitation by coating the carbonate nuclei as they form. Similarly, unstable carbonate associated with lime or lime and soda ash softening operations can be prevented from depositing by the addition of metaphosphate.

Corrosion associated with aggressive waters is inhibited by the addition of small quantities (0.5 to 2 parts per million) of metaphosphate to the water supply. After continuous application, a film of metaphosphate forms on the metal or metal oxide surfaces throughout the entire distribution system, as well as the household plumbing, which markedly reduces corrosion, tuberculation, and red water. The film protection appears to be effective at all *p*H values above 5.0, and, therefore, *p*H adjustment is usually not necessary.

The nature of the sequestration and protective film formation produced by metaphosphate is as yet not fully determined. The anhydride of phosphoric acid, phosphorus pentoxide, P_2O_5, combines with one, two, or three molecules of water to form, respectively, meta-, pyro- or orthophosphoric acid:

$$P_2O_5 + H_2O \rightarrow 2HPO_3 \quad \text{(meta-)}$$
$$P_2O_5 + 2H_2O \rightarrow H_4P_2O_7 \quad \text{(pyro-)}$$
$$P_2O_5 + 3H_2O \rightarrow 2H_3PO_4 \quad \text{(ortho-)}$$

The meta- and pyrophosphoric acids in solution undergo slow hydration to the completely hydrated ortho form. Metaphosphoric acid, because of its strong unsatisfied hydration capacities, can condense upon itself to form polymers of complex formation of the general form $(HPO_3)_n$. Hexametaphosphate is one of such forms with six molecules of the simple acid united $(HPO_3)_6$. Sodium hexametaphosphate is the sodium salt of such a complex, first developed for commercial use by Hall.* Sodium hexametaphosphate is known to

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* R. E. Hall, U. S. Patent 1,903,041, 1933; U. S. Patent 1,956,515, 1934.

form a complex with calcium, magnesium, iron, manganese, and other di- and trivalent ions, such that the metals are no longer cations but are combined with the metaphosphate radical as part of the anion. Thus sequestered, the metal ions lose all their former characteristics and are henceforth controlled by the metaphosphate complex.

The formation of protective film on nuclei of precipitates and on metal and metal oxide surfaces is not explained by this theory of sequestration. It is believed that the film formation is a liquid–solid interfacial adsorption phenomenon. Apparently the film serves as an effective insulator between the water and the metal.

Physiologically, hexametaphosphate applied to water supplies as a corrective treatment is nontoxic.* Even in relatively large doses, taken by mouth it is not more toxic than any physiologically active salt. By preventing the formation of calcium soap deposits, hexametaphosphate is beneficial to the cleansing of the hair and skin, a favorable factor in avoiding skin infections.

The addition of sodium hexametaphosphate to distribution systems and old lead plumbing connections is not a hazard. The action on lead is to reduce the amount taken up by waters of *p*H value lower than 7.0 and possibly to increase solubility slightly in waters of *p*H value greater than 8.0.† But since solubility of lead at *p*H values above 8.0 is very low, the slight increase is not dangerous. The protection afforded at low *p*H values is a distinct safeguard.

The use of metaphosphate in conjunction with detergents as an aid to cleansing is discussed further under the Food Contact, Vol. II.

TREATMENT DEFINED AS A COMBINATION OF PRINCIPLES

The foregoing descriptions of treatment processes have indicated rather clearly that the rapid-sand filter system is the central feature of treatment processes for waters intended for community supply. The same statement applies to a large extent to the treatment of industrial process waters and those for bathing pools.

It has been noted also that, in practice, there are many modifications employed to meet the particular needs of any specific situation.

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* K K. Jones, *J. Am. Water Works Assoc.,* **32,** 1471, 1940.

† E. W. Moore *et al.,* committee report, *J. Am. Water Works Assoc.,* **34,** 1807, 1942.

Some of these have been discussed; descriptions of others, of more limited scope, are to be found in the literature.

The modern science and art of water treatment can no longer be generalized and defined, simply by the name of a *system*. Treatment can be adequately defined only in terms of the combination of basic principles employed. The essence of good design and operation is the selection of that combination which insures the greatest and most consistent protection from harmful and objectionable pollution at the least cost.

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CHAPTER 15

TREATMENT OF POLLUTED WATERS

SEWAGE AND WASTES

PURPOSE OF SEWAGE AND WASTE TREATMENT

Sewage and waste treatment deals with the three major types of nuisance: physical, chemical, and bacterial (p. 395). Its primary purpose is the reduction of the nuisance features to desirable and practicable limits with reference to the intended uses of the receiving water. A sound and economical plan of treatment is based upon an evaluation of stream assets, including natural purification capacity, and pollution liabilities.

Furthermore this evaluation will take into consideration the probabilities of less favorable stream conditions occurring with low stream flows during droughts and will attempt to balance costs of the required additional plant to meet such contingencies as the likelihood of their occurrence. In brief, just as a physician makes a diagnosis before prescribing treatment, so the engineer evaluates stream conditions and needs before specifying remedial measures. In the development of the means he does not lose sight of the end; first and foremost, the objective of treatment is stream conservation.

A GENERAL CLASSIFICATION OF SEWAGE AND WASTE TREATMENT SYSTEMS

As with the treatment of water, the combination of principles employed in the treatment of sewages is dependent upon intended water uses and upon the nature, concentration, and physical state of the polluting matter present. This material is predominantly organic; its concentration is best expressed in terms of BOD; it is generally found in three physical states: suspended, colloidal and dissolved matter, in about equal proportions. A rational classification of treatment processes can be made upon the basis of the physical state of matter with which the process is particularly competent to

TABLE 52

General Classification of Sewage and Waste Treatment Systems

Treatment Process Commonly Known as	Usual Combination of Principles Employed	Removed by Treatment	Quality of Effluent	Classification of Treatment
(1) Sedimentation	1. Mechanical (screening) 2. Hydraulic separation	Suspended matter. BOD reduction 25 to 50%	Free of floating and sleek-producing matter. Free of matter producing sludge banks. Effluent containing colloidal and dissolved organic matter and high concentration of bacteria.	Primary
(2) Sedimentation and chlorination	1. Mechanical (screening) 2. Hydraulic separation 3. Disinfection	Same as no. 1 and bacteria.	Same as no. 1 except relatively low concentration of bacteria.	Primary
(3) Chemical precipitation (more properly, chemical coagulation).	1. Mechanical (screening) 2. Coagulation 3. Hydraulic separation 4. Disinfection	Suspended and colloidal matter and bacteria. BOD reduction 50 to 75%	Free of floating and sleek-producing matter. Free of matter producing sludge banks. Effluent clear and colorless and low in bacterial concentration, but containing dissolved organic matter.	Intermediate

(4) High-rate trickling filters	1. Mechanical (screening) 2. Hydraulic separation 3. Biological 4. Disinfection	Suspended and colloidal matter and bacteria. BOD reduction 60 to 75%	Same as no. 3.	Intermediate
(5) Trickling filters—conventional low rate (oxidation treatment)	1. Mechanical (screening) 2. Hydraulic separation (pre- and post-) 3. Biological 4. Disinfection	Suspended, colloidal, and dissolved matter and bacteria. BOD reduction 80 to 95%	Same as no. 3 except dissolved organic matter partly removed.	Complete
(6) Activated sludge (oxidation treatment)	1. Mechanical (screening) 2. Hydraulic separation (pre- and post-) 3. Biological 4. Disinfection	Suspended, colloidal, and dissolved matter and bacteria. BOD reduction 90 to 95%	Same as no. 5.	Complete
(7) Intermittent-sand filtration (oxidation treatment)	1. Mechanical (screening) 2. Hydraulic separation 3. Biological 4. Disinfection	Suspended, colloidal, and dissolved matter and bacteria. BOD reduction 90 to 98%	Same as no. 5 except very low concentration of bacteria.	Complete

deal. In the present chapter these various processes are grouped into treatment systems of three sorts: *primary treatment,* principally for the removal of suspended matter; *intermediate treatment,* principally for the removal of suspended and colloidal matter; and *complete treatment,* for the removal of suspended, colloidal, and dissolved matter. This classification is based upon end results, rather than upon the means employed. It therefore affords a basis, likewise, for the classification of effluent quality. Methods of treatment vary widely, but, from the standpoint of the receiving waters different means which accomplish the same end results should be classified as the same treatment. Table 52 is such a classification applied to some of the commonly named processes of treatment.

Full evaluation of any particular sewage or waste treatment works can be gained only by breaking it down into a combination of the basic principles of treatment employed. Likewise, in design, sewage and waste treatment cannot be generalized; each particular installation is based upon the use of that combination of principles which most efficiently removes the required portion of the pollution debt at the least cost. Accordingly, the three classifications of treatment systems set up will be analyzed with respect to the combination of principles employed, the practical basis of design and operation, and their efficiencies, advantages and limitations.

GENERAL BASIS OF FUNCTIONAL DESIGN OF WORKS. Sewage and waste treatment plants are designed for continuous-flow operation, and the units must be able to handle the expected variations in flow from day to day and from hour to hour. Treatment plants are rated, however, on the basis of *average daily flow,* and are usually designed with excess capacity based upon requirements *10 years hence* with provision for installation of additional units as increase in flow develops. The prediction of future needs should be conservative and should take into consideration the leveling off to stabilized population. Overdesign leads to expenditure for facilities which will never be required. Furthermore, excess capitalization should be conservative to take advantage of the rapid advances being made in the art and science of treatment.

Since the plant functions on a continuous-flow basis, the design load for any operation must be divided between at least two units so that, in the event of breakdown or overhaul for repair, the remaining unit can take the flow temporarily at higher rates.

PRIMARY TREATMENT

Principles and Flow Diagram. Primary treatment, as now defined, employs mechanical and hydraulic separation principles to which disinfection may be added as an adjunct. The major operating units used in this combination of principles are indicated in the flow diagram, Figure 105. The spent water supply of the community, collected in a sewerage system, is passed through screens and shredder or is comminuted (mechanical), and the grit, predominantly sand, is separated to avoid subsequent operating difficulties (hydraulic separation—differential sedimentation). The flow then passes to the major unit of the system, the sedimentation tanks, for the removal of suspended organic matter (hydraulic separation). Depending upon the bacterial requirements of the receiving waters,

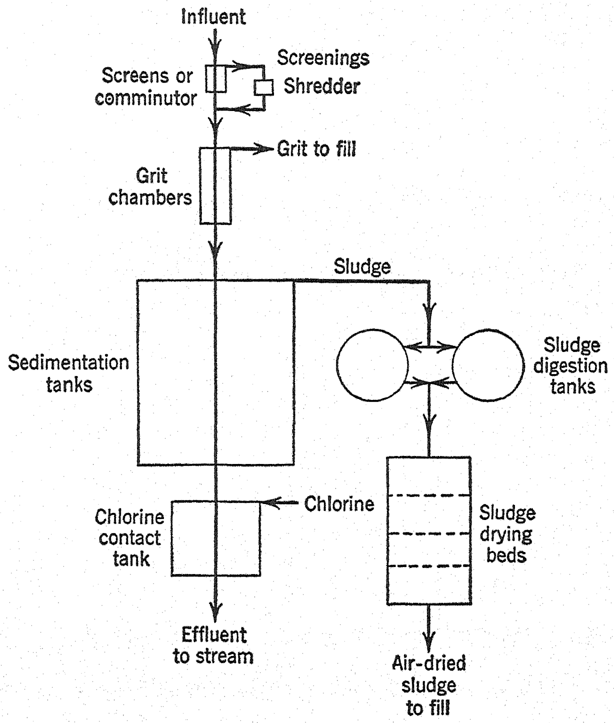


Fig. 105. Schematic flow diagram, primary treatment.

a chlorine contact unit may be provided for the reduction of bacteria, (disinfection).

UNITS

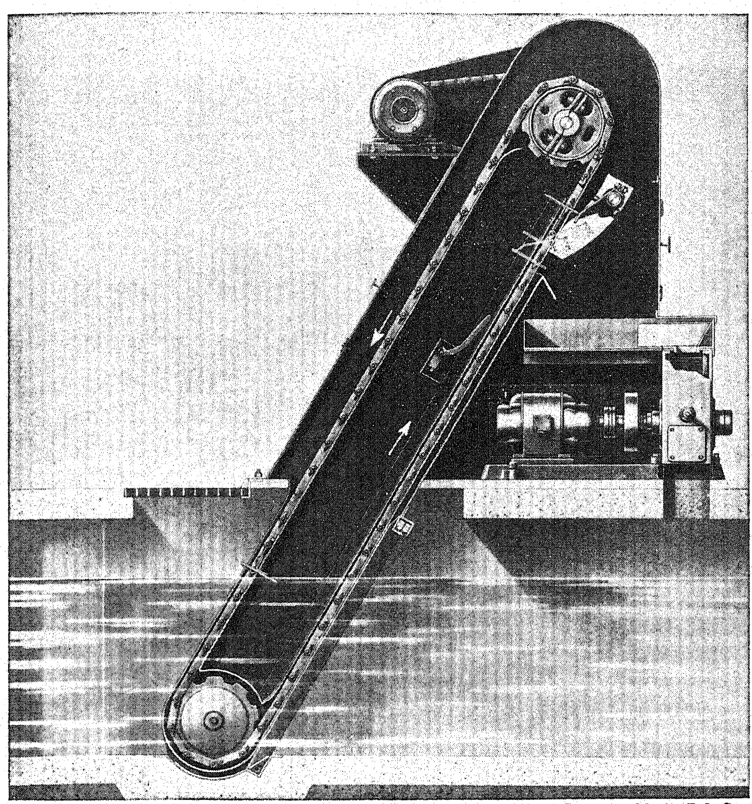
Screens and Shredders—Comminutors. The purpose of screens and shredders or comminutors is to intercept large suspended particles which would clog pipes and pumps and to shred the material into smaller pieces to facilitate handling with other suspended matter in the various treatment units. Screens comprise a rack of bars with 1-inch to 1½-inch spacings, usually equipped with a mechanical device to remove the intercepted screenings and elevate them to a position where they can be shredded (Figure 106). Several commercial prefabricated mechanical screens are available. To insure retention of the intercepted material, the screens are placed in a channel of sufficient width to provide a velocity through the net openings between the bars of not over 3 feet per second. The velocity in the channel preceding the screen is kept high enough during low flow to prevent the deposit of grit and organic matter.

Where size of plant warrants, screening capacity should be divided into two or more units, and in the smaller installations where a single mechanical screen is installed, it should be protected with a by-pass overflow channel equipped with a hand-cleaned rack. Comminutors (Figure 107) are equally suitable for the purposes served by screens and shredders.

Grit Chambers. Grit chambers are long narrow concrete channels 2 to 6 feet deep, 30 to 60 feet long, with a nominal detention period of 30 to 60 seconds. Where the sewerage system is of the combined type, the first flush of storm wash will carry substantial quantities of sand and cinders which must be removed by the grit chambers, so that the deeper longer channels are employed. With a separate sanitary sewerage system the shallower shorter channels suffice. The channels are usually provided with a mechanical scraping device to remove the deposited grit; or cleaning is accomplished by putting one channel out of operation, draining it, and removing the deposit manually.

Design of grit chambers is primarily a hydraulic problem. The velocity in the channel must be reduced sufficiently to allow differential sedimentation of the granular mineral grit without scouring it from the bottom of the tank (p. 434). A velocity of one foot per second is theoretically and practically indicated for the limitations of sand sizes desired to be removed.

Since the flow of sewage varies over a considerable range during the day and from day to day, means for compensating for these variations and for maintaining the velocity at the desired rate are essential. Three methods are commonly employed:



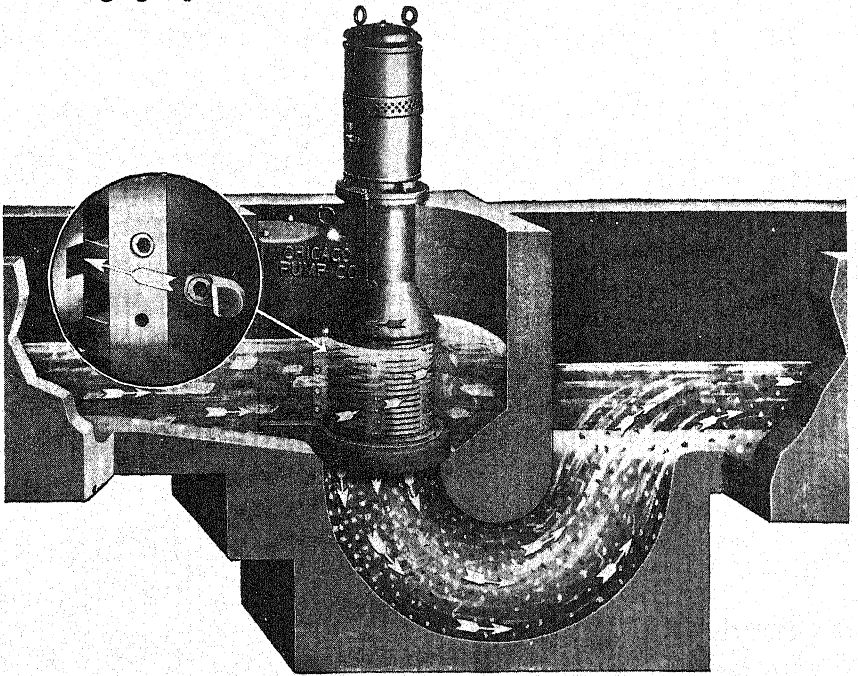
Courtesy Chain Belt Co.

Fig. 106. Screen and shredder.

A division of the maximum flow among several channels to permit dropping some out of service as flow diminishes.

Design of the cross section of the channel so that, as the depth of flow diminishes, wetted area will be proportional to the flow, thereby maintaining a constant velocity.

A channel of rectangular cross section, simple to construct, provided with a hydraulic control device in the outlet of the channel, such as a Parshall flume, the discharge of which varies approximately in direct proportion to the depth of sewage in the grit chamber, thereby maintaining practically a constant velocity, regardless of changing depth.



Courtesy Chicago Pump Co.

FIG. 107. Comminutor.

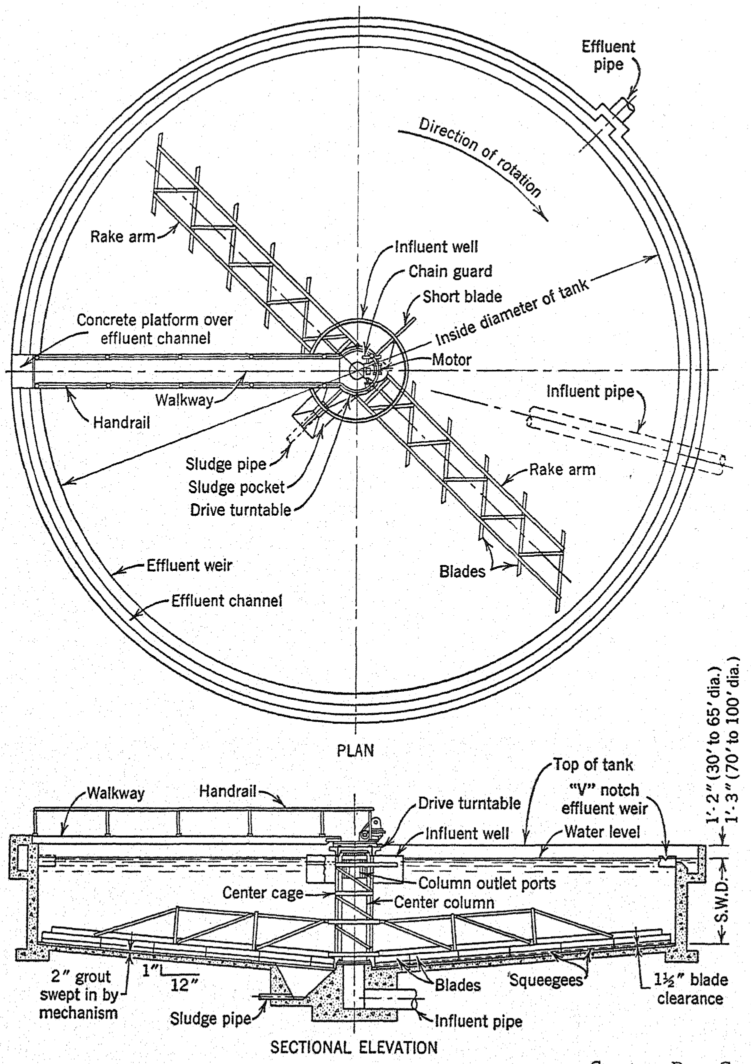
In practice, a combination of the first and third methods is most frequently used, designed to limit velocity variations between 0.95 to 1.05 feet per second and maintain minimum variations in depth. Incidentally, the hydraulic control device also serves as a meter to measure the flow through the plant, an essential feature for efficient plant operation.

SEDIMENTATION TANKS. Sedimentation tanks are constructed of reinforced concrete and may be either circular or rectangular. The combined capacity of the tanks should provide 2 hours theoretical detention, based upon the average daily design flow. Since the design flow is based on an estimated load 10 years hence, the detention period will be greater than 2 hours at all rates of flow below the design rate. However, since the design rate is average daily flow, during certain hours on days of high flow, the detention period may be less than the 2 hours for short periods. In earlier practice, 4 hours detention, based on rather optimistic predictions of future population were used with a result that the economic limit of sedimentation efficiency was exceeded. During periods of low sewage flow, in particular, the detention periods were so long that high dispersion with stratification, gave rise to septic conditions. This greatly reduced the efficiency in BOD removal, particularly when sludge was allowed to accumulate in the tanks. The present trend is toward shorter detention periods, with careful consideration of low dispersion and installation of continuous sludge and scum removal devices.

Several types of sludge-scraping devices are commercially available for both circular and rectangular tanks. In circular tanks, sludge is scraped toward a central sump in the bottom of the tank, while the floating solids and scum are simultaneously skimmed from the surface and swept into a scum sump at the periphery (Figure 108). In rectangular tanks, sludge is scraped into a sump at the bottom of the tank at the inlet end, while the floating solids and scum are skimmed to the outlet end and discharged into a scum gutter (Figure 109). With the exception of a shallow surface baffle to protect against discharging scum over the effluent weirs, baffles are seldom used in the newer installations, as they frequently induce dispersion, rather than correct it.

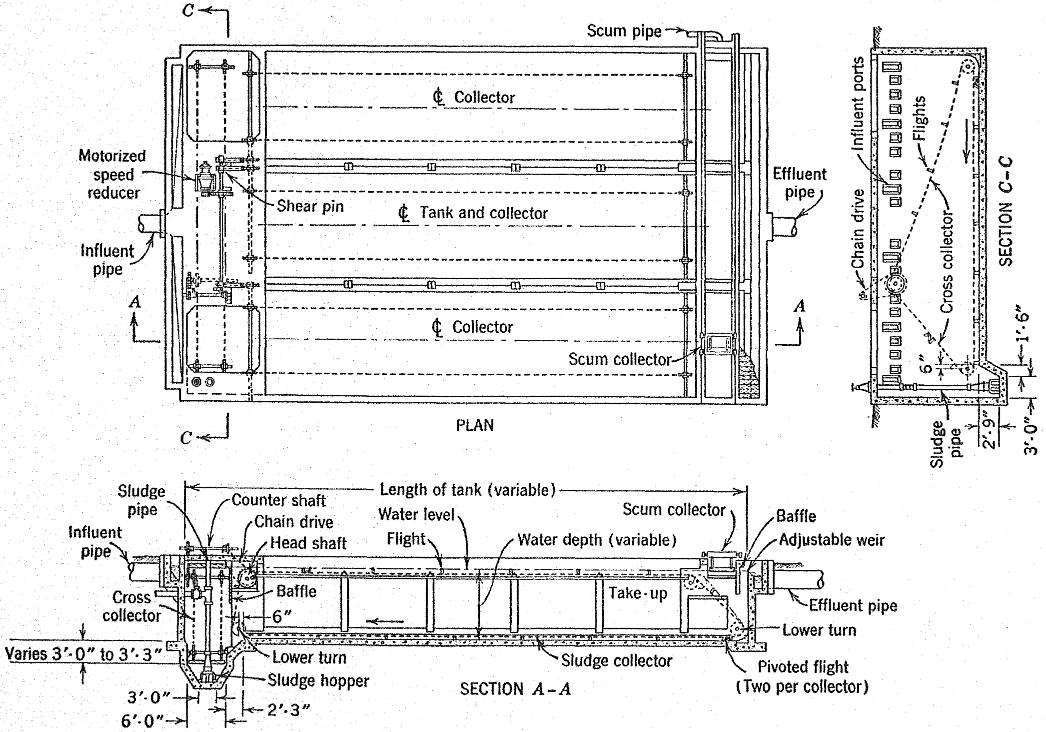
The dimensions of a particular installation, including inlet and outlet arrangements, must be carefully considered in relation to the factors which affect dispersion (p. 437). Provision of volume sufficient to afford the theoretical detention period without consideration of such factors as depth and relative position and types of inlets and outlets leads to wide variation in actual operating efficiency of tanks of different arrangements but of identical theoretical detention. The old deep tanks of 15 to 20 feet are giving way to shallower depths of 6 to 10 feet, although shallow depths and increased surface area alone do not assure a low dispersion index.

IMHOFF TANKS. For small installations a combination sedimentation and sludge digestion unit known as an Imhoff tank (Figure 110) may be substituted for the usual sedimentation tanks and



Courtesy Dorr Co.

FIG. 108. Circular sedimentation tank.



Courtesy ***Link Belt Co.***

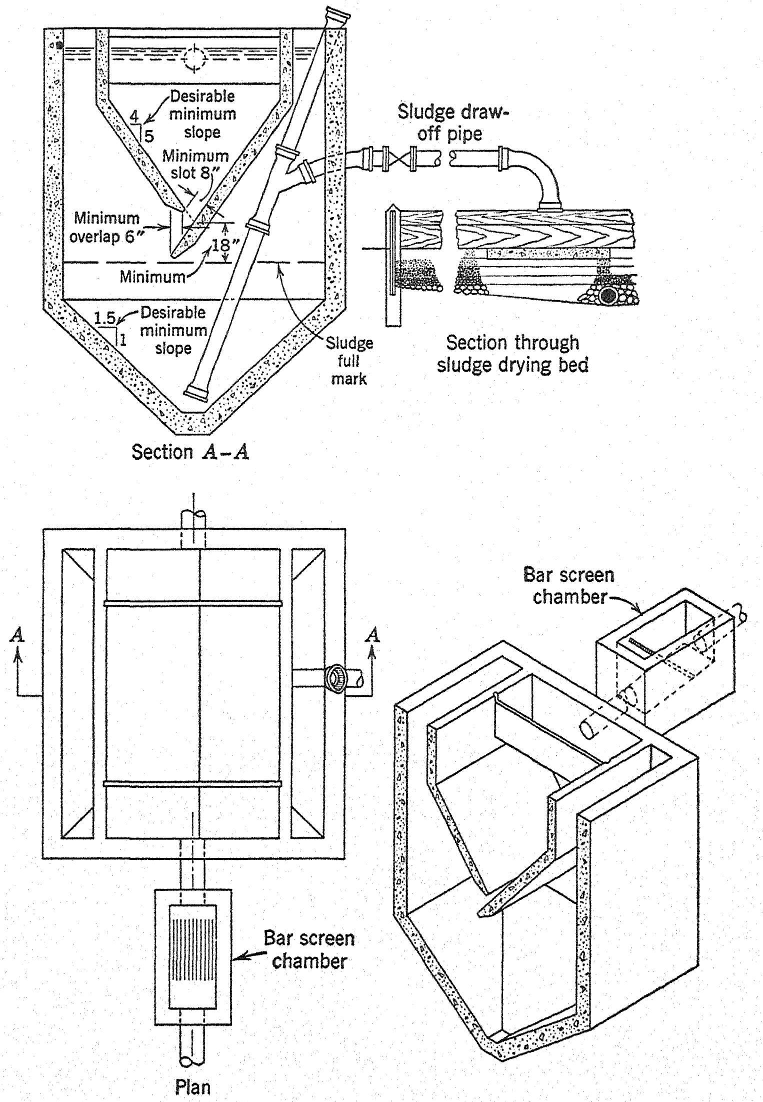
Fig. 109. Rectangular sedimentation tank.

separate sludge disposal facilities. Essentially, it is a tank within a tank, with a central portion serving as the sedimentation unit through which the sewage is passed. The suspended matter which settles on a sloped bottom slides through an open slot to the underlying compartment, which serves as the digestion chamber. The vertical enclosing walls form open channels, 18 to 24 inches wide, along each side of the sedimentation compartment, which serve as gas vents. The bottom of the digestion compartment is of hopper construction, from which digested sludge is withdrawn to sludge drying beds. Sufficient hydrostatic pressure is usually available to discharge sludge to the drying beds without pumping.

Imhoff tanks are simple in operation and require a minimum of attention, as no moving parts or special equipment are involved. They are best suited to warm climates where temperatures are sufficiently high to insure year-round digestion without artificial heating. In cold climates digestion is inhibited or ceases during the winter. When digestion again resumes with rise in temperature, the winter's accumulation of raw sludge usually results in acid digestion and violent foaming, which at times overflows the gas vents. Since the digestion and the flow-through sedimentation compartments are interconnected, it is not feasible to maintain digestion temperatures by artificial heating. Digestion difficulties can be ameliorated by providing substantial overdesign of digester capacity and by liberal use of lime to keep the digester alkaline.

The low operating cost of Imhoff tanks is offset to some extent by high construction cost, since it is a structure of considerable depth, complicating construction, particularly where ground conditions are difficult. The extreme simplicity of the Imhoff tank, which is an asset in small installations treating strictly domestic sewage, limits flexibility in operating control, essential in larger works treating both sewage and industrial wastes.

CHLORINE CONTACT TANKS. A contact period, 15 to 30 minutes, based on average daily flow, is usually provided. If this is not available in the outfall sewer, chlorine contact tanks are installed. In the interests of economical construction, a single tank approaching square dimensions, equipped with *around-the-end* wooden baffles, is provided. The channels between baffles should provide sufficient velocity (0.3 foot per second), to prevent deposit of fine suspended matter carried through from previous operating units. The long



Courtesy Russell and Axon, Consulting Engineers

Fig. 110. Typical Imhoff tank.

path of travel provided by around-the-end baffles also insures a low dispersion index, thereby more nearly insuring the theoretical detention period.

Chlorine solution is admitted through a suitable diffusion manifold at the entrance to the tank, arranged to insure intimate mixing with the treated sewage. It may be found desirable to provide for prechlorination by introducing chlorine at the inlet end of the plant where it is an effective agent in controlling odors. Where prechlorination is practiced, the contact period for postchlorination of the final effluent may be reduced to 15 minutes detention.

Chlorinators and auxiliary facilities are similar to those provided for water treatment except that they are larger in view of the higher chlorine demand of the sewage.

OPERATION

Operation of a primary treatment plant is simple and, to a great extent, automatic. Screens can be set for periodical self-cleaning, and screenings can be shredded once daily and returned to the sewage flow. Comminutors are completely automatic. The earlier practice of removing screenings for burial or incineration is being replaced by the installation of shredders.

Grit removal is accomplished by occasional operation of scraping devices with continuous operation during storms, when grit accumulations are heavy. The grit is scraped to a sump at the inlet end of the channel, from which it is elevated usually by a worm conveyor, operated three or four times a day, discharging into containers or hoppers. Since grit is predominantly mineral matter, it can be disposed of without danger of odor nuisance as fill at any convenient location. Shallow covering, however, is desirable.

Sludge deposited in the sedimentation units is removed by the sludge scraping devices which may be operated continuously or at intervals during the day. Sludge should be withdrawn at least once and preferably three times a day from the sludge sumps to its disposal system. If sludge is allowed to accumulate in the tanks, digestion will be started, as evidenced by the appearance of gas-lifted masses at the surface. This reduces the efficiency of sedimentation and gives rise to odors. Similarly, the surface of the tank should be kept free of floating material and scum formations by continuous or frequent intermittent skimming. Accumulated scum is flushed to a sump or trough from which it is withdrawn for disposal with sludge. The tank inlet and outlet channels should be kept free of deposits and occasionally the tank walls flushed and scraped at the water line to remove accumulations of grease.

Operation of the chlorination system is similar to that described for water treatment (p. 508), but the dose is usually substantially greater. Where prechlorination is practiced on raw sewage, dosage may range from 15 to 20 parts per million, depending upon the freshness of the sewage and its chlorine demand. Postchlorination of primary effluent will require from 5 to 10 parts per million to satisfy demand and provide a residual of 0.2 to 0.5, after 30 minutes contact. The problem of taste and odor is not a factor in sewage effluent chlorination, but economy dictates avoidance of excessive residuals.

Sludge disposal, the major operating problem of a primary treatment plant, is discussed subsequently (p. 597).

EFFICIENCY, ADVANTAGES AND LIMITATIONS OF PRIMARY TREATMENTS

The efficiency of primary treatment is limited to the removal of that portion of pollution which is in the suspended state, and, therefore, the effluent still contains the colloidal and dissolved organic load. The efficiency in removal of suspended matter ranges between 50 and 70 per cent, depending upon the concentration of suspended matter present and the detention period provided for sedimentation. The corresponding reduction in load, measured as BOD, is less, 25 to 50 per cent. The removal of a high percentage of suspended matter, constituting the floating and settleable solids, is the most economical method of preventing unsightly surface sleeks and detrimental sludge deposits in the receiving waters. Where oxygen resources of the receiving waters are high, primary treatment may provide sufficient reduction in BOD to meet stream requirements.

The advantages of the primary treatment system are its simplicity of operation and its relatively low capital and operating costs. On the other hand, it is not a flexible treatment and is definitely limited in its efficiency in BOD reduction.

COMPLETE TREATMENT

Principles. Complete treatment, accomplishing the removal of suspended, colloidal, and dissolved matter, must rely upon applicafor removing dissolved organic matter. Mechanical principles, hydraulic separation, and disinfection are utilized in secondary roles.

The biological principles can be employed in two ways. One involves passing the sewage through a stationary biological bed, which houses the essential zoogloea (trickling filters), and the other, passing the zoogloea through the sewage (activated sludge).

TRICKLING FILTERS

In the trickling filter system (Figure 111) after the usual preliminary treatment of comminuting or screening and shredding (mechanical principles) and grit removal (hydraulic separation), common to all systems, the settleable solids are removed in primary sedimentation tanks (hydraulic separation). The clarified effluent then passes to a dosing tank for application to trickling filter beds.

The sewage is applied to the bed in the form of a spray, well distributed over the surface. It trickles over the stone or other medium and through the thin film of biological growth which coats the stones and is held in the interstices. The fine nonsettleable solids, the colloids, and most of the dissolved organic matter are withheld by adsorption or mechanical attachment and subjected to biochemical oxidation (biological principles).

The effluent carries the products of oxidation, the residue of partially oxidized matter and the finely divided residual humus-like material which has sloughed from the stone surfaces. This self-cleansing characteristic of the trickling filter is one of its chief advantages. Because of it, however, the effluent is never clear and must be subjected to postsedimentation (hydraulic separation).

The clarified effluent from the final or postsedimentation unit may be subjected to chlorination (disinfection principle) before discharge.

UNITS. Comminutors or screens and shredders, grit chambers and preliminary sedimentation units with sludge and scum removal devices are similar to those described for Primary Treatment.

The biological beds are housed in circular or rectangular tank units. On the floor is a special *underdrain* system consisting of precast channel blocks slotted at the top to receive the liquid trickling through the stone from above, and internally comprising a channel of sufficient size to serve simultaneously as a collecting conduit for the liquid and as a ventilating duct to admit air to the bed. The channels, formed by the underdrain system, discharge to a collecting conduit leading to a valved outlet. The *stone* (or other medium)

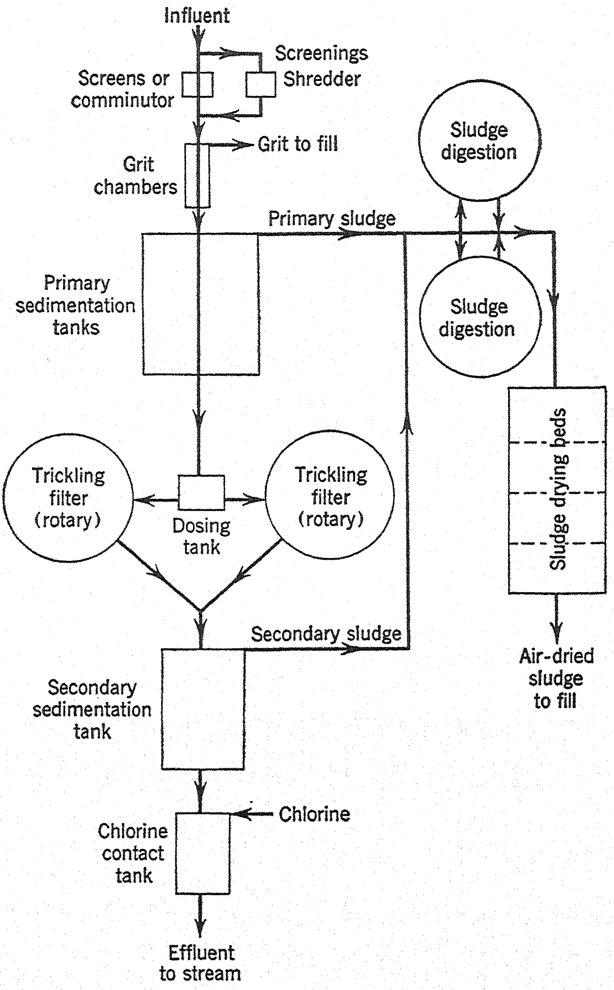


Fig. 111. Schematic flow diagram, complete treatment, trickling filter.

rests upon this underdrain system and provides the housing in which the biological growths develop and function.

Since a biological bed must breathe throughout its depth, an adequate air supply is provided by connecting the underdrains to pipe vents spaced at intervals around the periphery of the bed. The natural chimney action induced by temperature difference within and without the bed produces adequate circulation of air. The *filter medium* may be any durable weather-resistant material such as crushed stone, gravel, or slag. A homogeneous bed of uniform-sized particles, free of dust and fines, is essential. In size the medium should not be less than 1 inch nor over 3 inches; smaller sizes interfere with sloughing (self-cleaning), and larger sizes do not provide adequate contact nor retain sufficient growth within the interstices.

Before dealing with area and depth requirements for any desired efficiency, it will be helpful to consider the nature of the variation in the performance of biological beds through successive increments of depth. The rate of extraction of organic matter per interval of depth of a biological bed is proportional to the remaining concentration of organic matter measured in terms of its removability. This, it is recognized, is similar to the biological oxidation law (p. 309) and may be expressed in differential form as

$$-\frac{dL}{dD} = KL$$

This integrates to

$$\log_e \frac{L_D}{L} = -KD$$

or

$$\log \frac{L_D}{L} = -0.434KD = -kD$$

whence

$$\frac{L_D}{L} = 10^{-kD}$$

L represents the total removable fraction of BOD; D is depth; and L_D represents the corresponding quantity of removable BOD remaining at depth D. The ratio L_D/L is the proportion of the total removable fraction remaining in the passing liquor at depth D and $1 - (L_D/L)$ is the proportion extracted.

Not all of the BOD applied to a biological bed is removable, and, hence, there is a residual which is not extracted even by repeated passages or by a very deep bed. The magnitude of the total removable fraction is dependent on a combination of variable factors.

The BOD in dissolved form is the most difficult to remove and requires protracted intimate contact with zoogloea for its extraction. The removable fraction L is dependent, therefore, on the proportion of the BOD in suspended and colloidal form as distinct from that in true solution.

The mass of the zoogloea in the bed and its sloughing, as well as the extent and duration of contact, are dependent on the hydraulic rate of passage of the liquid medium through the bed. The removable fraction L can be expected to decrease as the rate of application in mgad* increases. This is demonstrated by the performance for continuous application to high-rate beds and is confirmed for intermittent application by the experimental work of Levine and Associates.†

Obviously, there must be some limit to the quantity of BOD which can be assimilated by the biological life of the bed. The limiting BOD load, then, must be a function of the rate of biological oxidation and storage capacity for accumulation of BOD within the bed. If the rate of extraction from the applied load exceeds the rate of assimilation, then accumulation will reach a point where bed storage capacity of the zoogloea is exceeded, and the excess will be carried through, thereby increasing the residual in the effluent and decreasing L. Obviously, also, the size of the medium (surface area per cubic foot) is a factor in the storage capacity.

Since biological oxidation is a temperature function, the limiting load is lower during cold weather; however, at loadings which come to equilibrium at levels below the limiting storage capacity of the bed, L is unaffected by temperature and is constant for any applied load below the limiting load. With sewage of normal strength, the influence of hydraulic rate of passage will begin to produce a decrease in the removable fraction L, before the limiting BOD load is reached. Increased hydraulic and BOD loadings at a lowered level of removability are discussed later under high-rate beds.

The logarithmic rate of extraction k and the magnitude of the removable fraction L for low-rate intermittent beds intended for complete treatment are determined from observed performance. Observations at 2-foot intervals in a 10-foot bed reported by Buswell and Associates‡ and performance of conventional filters reported by

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* Million gallons per acre of bed area per day.

† M. Levine, *et al.*, *Sewage Works J.* **8**, 701, 1936.

‡ A. M. Buswell, *et al.*, *Illinois State Water Survey Bull.* **26**, 1928.

Childs and Schroepfer* and by the Committee on Sanitary Engineering, National Research Council† indicate values approximately 0.175 for k and 0.9 for L, with hydraulic rates of 2 to 6 mgad. The applied BOD is settled sewage and the removable fraction is based on the combined action of the filter and its final sedimentation tank. These values are subject to refinement as more data become available but may be used to represent average performance.

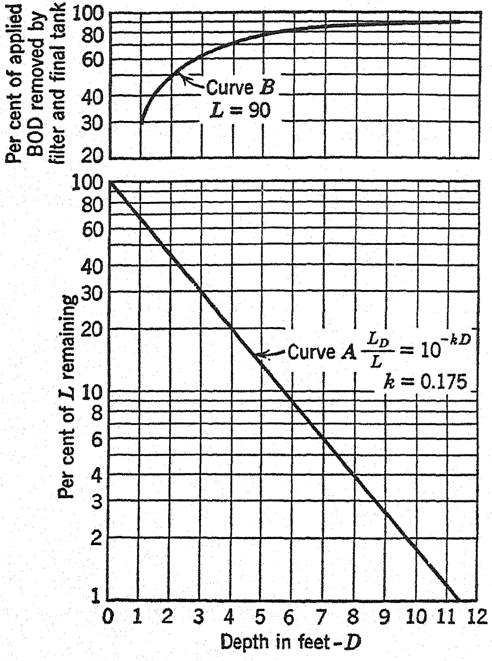

FIG. 112. Relation between bed depth and performance of low-rate trickling filters. 2 to 6 mgad.

Figure 112 is a graphical representation of expected performance of standard low-rate filters. Curve A represents the basic law and shows the percentage of the total removable fraction L which remains in the liquor after passage through depth D; while curve B shows the removal effected in passage through depth D expressed in

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* J. A. Childs and G. J. Schroepfer, *Civil Eng.* **1**, 1391, 1931.

† National Research Council, Subcommittee on Sewage Treatment of the Committee on Sanitary Engineering, *Sewage Works J.* **18**, 791, 1946.

terms of BOD load applied to the bed. The curves express removal in terms of the combined performance of the filter and its final sedimentation tank, and the applied load is in terms of settled sewage. Depth of bed is determined by the efficiency of removal desired, and area of bed is determined by the allowable limit of BOD load and hydraulic rate of passage per unit of bed area. Since no gain in removal of BOD is obtained by increasing bed area, the most economical designs are obtained with BOD and hydraulic loadings at or just below the limit at which *L*, the removable fraction, is adversely affected.

Most regulatory agencies place the limit of hydraulic loading between 2 to 6 million gallons per acre per day and of 5-day BOD (settled sewage) at 1500 to 7500 pounds per acre per day.* In light of the experience with high-rate filters, these limits are on the conservative side, and, as more data become available at higher loadings, they may be increased. For efficiencies required in complete treatment, the minimum depth most commonly specified is 6 feet. This is consistent with curve *B*, Figure 112, and, since the efficiency curve flattens decidedly with depths over 6 feet, it appears uneconomical to use depths greater than 8 feet.

The performance or design of conventional low-rate trickling filters can be evaluated readily by means of Figure 112 as in the following example:

Sewage flow, million gallons per day	4
5-day BOD	
Parts per million	225
Pounds per day	7150
Stream conditions allow, pounds per day	770

If a daily BOD loading of 7500 pounds per acre is allowed and removal of BOD by primary treatment of 30 per cent is assumed, a removal of 85 per cent of the load applied to the trickling filter (5000 pounds) will be required to meet the stream conditions.

Curve *B* indicates a filter depth of 7 feet for this degree of removal. The corresponding area will be 5000/7500 or 0.667 acre. This area will call for a hydraulic loading at the rate of 6 mgad, which is within the permissible limit. If this had not been so, a larger area

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* The practice of specifying loadings volumetrically in terms of pounds per acre per day per foot of depth or in pounds per cubic yard assumes equal efficiency of removal at all depths, which is not consistent with theory and demonstrated performance at different depths.

but of the same depth would be specified. Whereas the size of the trickling filters is based primarily upon the BOD loading, the corresponding volume of sewage flow, which carries the BOD load, is an important feature in the hydraulic design of the dosing tanks and the distributor spray devices. The trickling filter operates intermittently. The necessity for this intermittent dosing, followed by a period of nondosing, arises from the problem of distribution rather than from any inherent advantage in a supposed *rest* period. In fact the ideal condition, from the point of view of the biological agencies at work, would be a uniform continuous feeding.

The total amount of sewage to be applied to a square foot of bed surface per hour, however, is so small that it is almost mechanically impossible to distribute it uniformly over the area and through time. Maximum uniformity of areal distribution is of primary importance in order to utilize the full bed capacity. To attain it, uniformity in time is sacrificed.

Application is accomplished by means of a dosing tank, which may require 10 minutes to half an hour or more to fill, and which empties in a few minutes through an automatic siphon to stationary spray nozzles fed from a grid distribution system (Figure 113). Alternatively, dosing may be accomplished through rotary multiple-arm distributors with multiple outlets. An arm of such a distributor may pass over a given spot on the surface every 5 seconds or so (Figure 114). These short-interval waves of sewage are much damped as they pass into the body of the filter, so that, within a short distance from the surface, the flow is essentially continuous during dosing.

Spray nozzles are tapped from the distribution mains at frequent intervals so spaced as to provide a uniform distribution of sewage to all portions of the bed surface in an umbrella-like spray. The head requirements and proportioning of pipe sizes and dosing tank serving a field of nozzles constitute an intricate hydraulic problem.*

Rotary distributors comprise pipe arms, usually 4, held approximately 12 inches above the surface of the stone by a central supporting column with cable ties. A series of downspray outlets are spaced along one side of each pipe arm, closely spaced toward the periphery and farther apart toward the center, to provide a uniform spray to all portions of the bed. Rotation is induced by the reaction of the discharge, similar to that of a lawn sprinkler, or by a water motor

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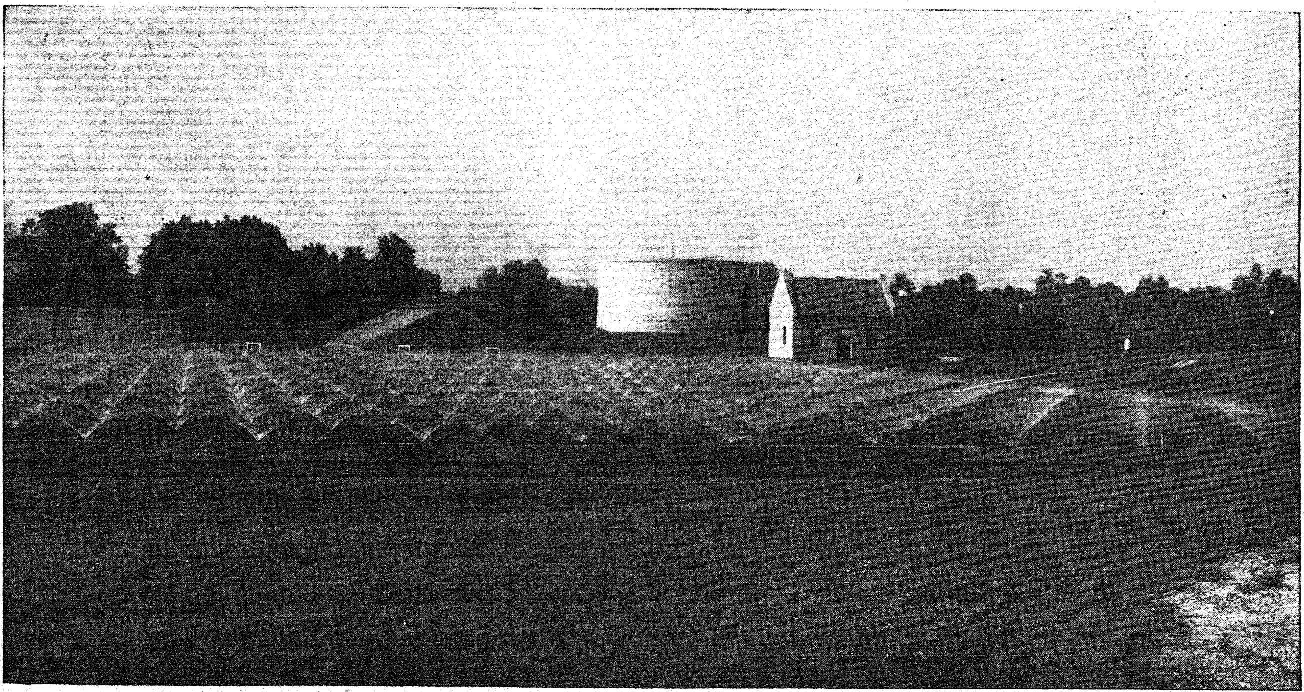
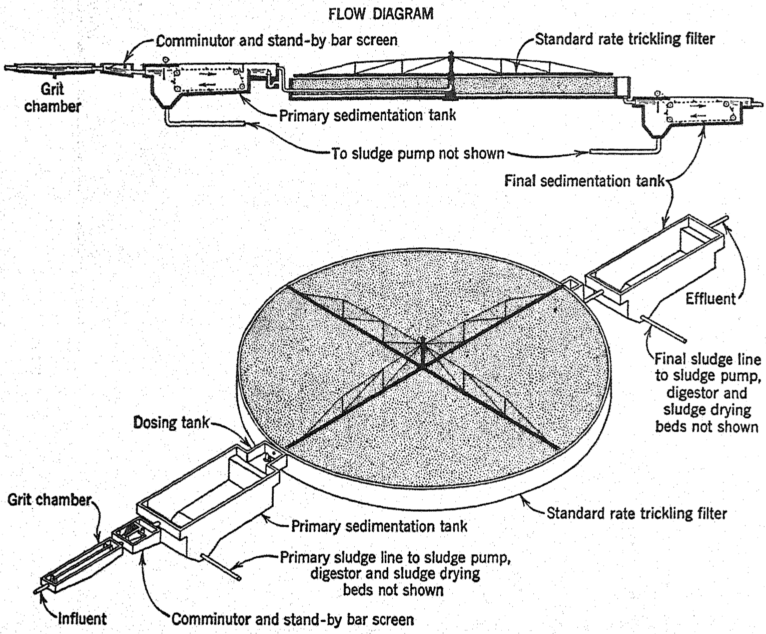
* See *Pacific Flush Tank Co. Bull.* 30.



Courtesy Pacific Flush Tank Co.

FIG. 113. Trickling filter, nozzle-spray type.

actuated by the sewage flow. Rotary distributors are commercially available for any diameter of bed up to 150 feet; larger diameters are difficult to support. The liquid is admitted to the distributor arms at the central column support, and, hence, the piping arrangements are much simpler and require less head than nozzle spray grids.



Courtesy Russell and Axon, Consulting Engineers

FIG. 114. Trickling filter, rotary type.

The head required to operate a trickling filter is substantial, as the sewage must be elevated to the dosing tank and then has a free fall through the bed into the underdrains and collecting conduit, leading to the final sedimentation tanks. This constitutes a total loss of head, from the maximum level in the dosing tank to the level of water in the final sedimentation basins, usually ranging from 13 feet to 17 feet for nozzle spray layouts, with 6 feet depth of stone, and approximately 4 feet less, where rotary distributors are employed. The head requirements are important, therefore, in the economics as well as the hydraulics of design.

Design of the final sedimentation tanks and the chlorine contact tanks is similar to that provided for primary treatment, except that a one-hour detention period, based upon average daily design flow, is adequate for the postsedimentation basins.

OPERATION. Since trickling filters operate as biological processes, a new installation requires a *maturing* period to build up the zoogloea within the bed. This may require 1 to 3 months, depending upon the season of the year. After a bed is established, however, very little operating control is necessary.

The biological population must be fed regularly; consequently, service of the beds cannot be discontinued for protracted periods and again resumed. Overfeeding with high BOD loads or suspended solids from poor preliminary sedimentation may cause clogging. Unequal distribution over the bed area may overload portions and again induce clogging.

Seasonal temperature variations affect biological activity, and in winter operational difficulties may result in decline in efficiency. Maintenance difficulties are chiefly nozzle clogging or freezing. Where climate is severe, portions of the bed surface may ice up, particularly around nozzles where the spray is low and weak.

Trickling filters are subject to odor and fly nuisances. Odor is best controlled by prechlorination with sufficient dosage to oxidize any hydrogen sulphide present, but not to carry a heavy residual to the beds. In plants which are overdesigned, prolonged detention in preliminary sedimentation tanks may develop septic conditions giving rise to odors during spraying.

Filter flies (*Psychoda*) breed in the upper layers of the beds and, unless kept under control, will emerge in annoying numbers. The larvae can be killed by flooding the bed for 12 hours. Where the underdrain vent system permits, the outlet is closed and the bed allowed to fill until the surface stones are submerged. The bed is drained gradually in order not to induce heavy sloughing and then placed in normal operation. If beds cannot be flooded, application of chlorine to the surface of the stone is effective, but care must be exercised not to overdose, or the filter growths will be adversely affected. DDT has been tried experimentally with some success.

At certain periods of the year, particularly in spring and fall, the beds will undergo heavy sloughing or *unloading*. The effluent will contain an unusual quantity of suspended matter, and efficiency may fall below normal for a period of several days. Unloading may also be induced by protracted heavy doses of toxic industrial wastes, but ordinarily the beds can successfully handle sudden shock loads of considerable variation in strength or character.

The small quantity of sludge removed from the final sedimentation tank is humus-like in character and quite well stabilized. It is usually returned to the primary sedimentation units where it resettles with the primary sludge and is withdrawn for disposal.

ACTIVATED SLUDGE

FLOW DIAGRAM. The flow diagram for complete treatment by activated sludge is shown in Figures 115 and 116.* After the preliminary treatment outlined for the trickling filter, the sewage is ready for the characteristic operation of this process, contact with the biological zoogloea (activated sludge). The sludge is returned from the final sedimentation tanks (*return sludge*) and mixed with the sewage at the inlet end of the aeration tanks, forming the *mixed liquor*. The sludge is swept through the sewage and supplied with oxygen by air diffusers placed along the channels of the aeration tanks. With a contact period of 4 to 6 hours, 85 to 95 per cent of the total (suspended, colloidal, and dissolved) organic matter is taken up by the activated sludge, leaving at the effluent end of the aeration tanks a mixture of highly purified water and suspended sludge containing the impurities. This mixture passes to final sedimentation tanks where the activated sludge is deposited (hydraulic separation), and a sparkling clear effluent is discharged. It may then be passed through a contact chamber for chlorination prior to final discharge to the receiving stream.

UNITS. Comminutors or screens and shredders and grit chambers are similar to those provided for primary treatment.

The preliminary sedimentation units are designed for a detention period of one hour, based upon average daily design flow, and are equipped with sludge and scum removal devices. Some installations introduce a short period (5 minutes) of diffused aeration preceding the sedimentation unit to aid in the flotation of grease. Oil and grease removal are important in the prevention of clogging of the air diffusers in the aeration chambers.

Aeration tanks are usually designed for a detention period of 4

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* Figure 116 is diagrammatic. The rolling motion of the sewage is transverse as it passes down the length of the aeration tank.

to 6 hours, based upon average daily design flow, plus an allowance of an additional 25 per cent for return sludge. Strong sewages and

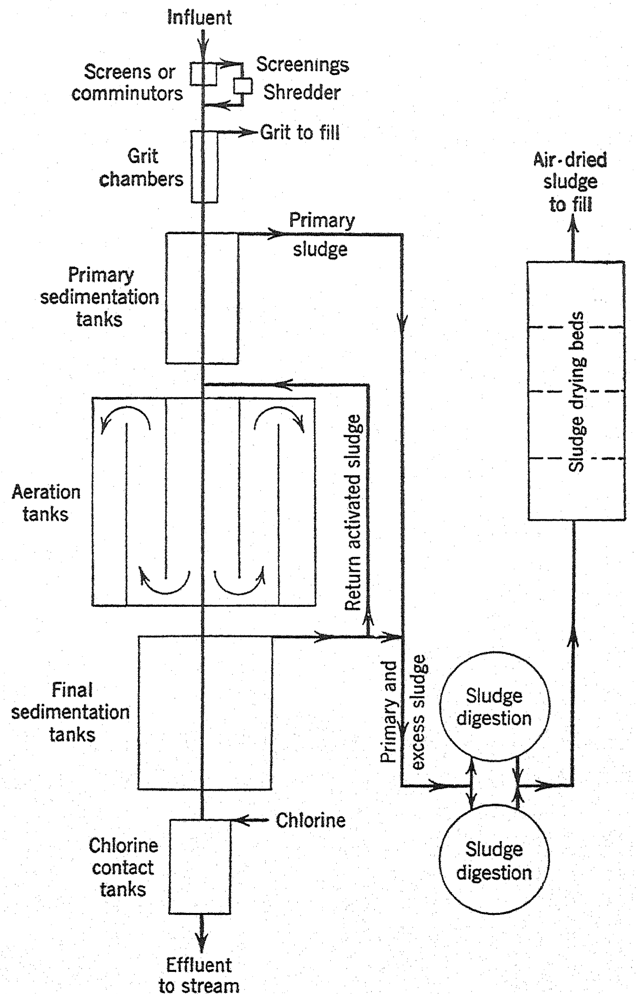
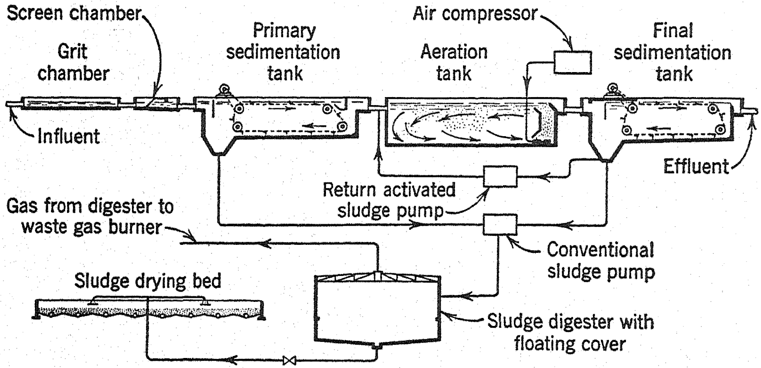


FIG. 115. Schematic flow diagram, complete treatment, activated sludge.

high reductions require the longer contact time, whereas the shorter aeration periods are satisfactory for weaker wastes. Two or more units are provided for flexibility in operation. Each tank is generally divided into 2 to 4 passes or channels (depending upon size), thus providing a long narrow passage, which reduces short circuiting. Width of channels should not exceed 1 to 1½ times the depth, to insure good mixing. Depth of the channels ranges from 10 to 18 feet, the shallower for small plants, the deeper for large installations. The depth affects the air pressure required to serve the diffusers located in the bottom of the channels and must be considered, therefore, in connection with the design of air supply. The channels are filleted at the bottom and flared at the top to aid in producing a spiral roll.



Courtesy Russell and Axon, Consulting Engineers

FIG. 116. Activated sludge system.

Porous fine-grained air diffuser plates, one foot square, are placed longitudinally along one side of each channel bottom, arranged in holders under which compressed air is admitted. The fine spray of air bubbles induces a spiral roll as the sewage and activated sludge pass along the channel. Aeration serves the dual purpose of sweeping the activated sludge through the sewage and of providing the oxygen required for biochemical oxidation. The plate area should be approximately 10 per cent of the tank bottom. The plates are set in precast holders in a single or double row and are divided into units of approximately 10 plates served by a valved air line.

Some installations use porous tubes placed above the bottom along one side of the channel, arranged in units attached to a swivel jointed air supply line. This permits elevating an assembly of tubes for cleaning without interrupting operation of aeration tanks. Other diffuser systems, referred to as ridge and furrow type, either transverse or longitudinal, have been employed, but spiral flow types predominate.

Although compressed-air diffusion systems are most frequently used, other commercial systems are available which induce circulation and aeration by surface agitation, either by paddle or brush agitators or by surface sprays. The paddles are located along one side. They induce a spiral roll, and oxygen is obtained by absorption from the atmosphere at the surface. The spray type, which is particularly adaptable for small installations, comprises a central draft tube located in a hopper tank. Above the draft tube at the surface is a motor-driven revolving disk which sends a spray outward over the surface, inducing circulation and providing aeration of the spray. One commercial system employs both submerged paddle wheels and compressed air diffusion.

The air supply is an important adjunct to the aeration tanks. Centrifugal or rotary air blowers, filters, and meters are located in an operating building, and air, under pressure, is distributed in pipe mains to the aeration tanks. Feeder lines, with hand-operated regulating valves, tap the mains and lead to the individual submerged batteries of diffuser plates or tubes. The air pressure or head required at the blowers is the equivalent of the depth of water in the aeration channels over the diffuser plates plus the losses in the feeders and air mains, which are generally 20 to 30 per cent additional. The quantity of air required ranges between 0.5 and 1.0 cubic feet of free air per gallon of sewage of average strength and may be as high as 2.0 cubic feet for strong sewages.

The air supply must be free of dust and dirt to prevent clogging of the fine porous diffusers, and, hence, the blowers are preceded by air filters through which the air is drawn from the atmosphere. Venturi meters or other air-flow measuring devices are installed in the discharge lines to measure the quantity of air supplied to each aerator.

An essential feature of the aeration tanks is the return sludge lines and pumps which regulate the quantity of activated sludge returned to the aeration tanks from the final sedimentation tanks. The sludge pumps, meters, and valve controls are usually housed in an operating gallery located between the final sedimentation tanks and the aerator tanks. These pumps are used also to discharge excess sludge to the location of the sludge disposal works.

The quantity of sludge to be handled will vary over a wide range, depending upon its water content. The volume of sludge returned to the aeration tanks also varies. Consequently, sludge pump design must provide flexibility.

The final sedimentation tanks, although similar to the usual tanks, generally provide a detention period of 1½ to 2 hours, based upon the average daily design flow plus 25 per cent allowance for the returned sludge. The activated sludge in the mixed liquor coming from the aeration tanks is light and flocculent in character, and its subsidence by sedimentation is greatly influenced by factors promoting dispersion. A low rate of discharge over surface effluent weirs is advantageous to avoid discharging fine floc. The sedimentation units are equipped with continuous sludge removal devices.

Chlorination equipment and chlorine contact tanks are similar to those described; the tanks usually provide 30-minute contact detention periods, based on an average daily design flow.

OPERATION. Activated sludge treatment is a delicate process and requires constant skilled supervision. The major operating problems center around maintaining proper activity or condition of the sludge and the control of the quantity returned to the aeration tanks. The quantity is difficult to measure, as its water content varies widely from hour to hour. Solids may range from 3 per cent to as low as ½ per cent (97 to 99.5 per cent water). Obviously, to provide a stated amount of actual zoogloea (dry solids basis) requires twice as much, in volume, of a 1 per cent as of a 2 per cent sludge.

Four methods are in common use to assist in the control of quantity of activated sludge introduced in the aeration tanks:

1. Volumetric ratio, return sludge to incoming sewage (about 25 per cent).

2. Volume of sludge in the mixed liquor. A liter sample is collected at the outlet of the aeration tank and settled 30 minutes in a liter-graduated cylinder, and the volume occupied by the sludge is recorded in per cent. This is a measure of the bulk of the sludge (10 to 20 per cent, average 15 per cent).

3. Weight of sludge in the mixed liquor. The suspended solids in the mixed liquor are determined in parts per million or in per cent dry weight (1800 to 3600 parts per million; practice varies widely).

4. Sludge index, ratio of volume to weight of sludge in the mixed liquor. (The volume in milliliters occupied by 1 gram of sludge, dry weight, after 30 minutes settling):

$$\frac{\text{Per cent volume [as determined in (2)]}}{\text{Per cent weight [as determined in (3)]}} = \text{sludge index}$$

Usual range of index 50 to 100

The condition of the return sludge is also important. It must be *active,* that is, must have the capacity to adsorb the suspended, colloidal, and dissolved organic matter contained in the sewage through which it is swept. Loss of activity of sludge is associated with:

1. Overfeeding the zoogloea with BOD (too small a quantity of mass in relation to concentration of organic matter in the waste being treated).
2. Underfeeding (the return of too large a quantity of zoogloea in relation to the concentration of organic matter in the liquor being treated).
3. Inadequate air supply to maintain aerobic activity.
4. Weakening of the aerobes by sudden slugs of toxic industrial waste or acids and alkalis.

Loss of activity of sludge is evidenced by poor purification, odor, poor settling characteristics, and, in extreme cases, *bulking* (extremely high sludge index). A bulking sludge will not settle in the final sedimentation tank; consequently, a tremendous volume of very thin sludge is on hand, and much of it escapes in the final effluent. Chlorination, excessive aeration, and dilution are variously used to correct bulking, but frequently normalcy cannot be established until the "sick" sludge has been flushed out of the system and new active sludge developed.

Types of organisms in the sludge determined by microscopic examination are an operating indicator of condition of the sludge.* Freedom from filamentous organisms (*Sphaerotilus*) and a preponderance of large ciliates indicate good sludge. The development of the filamentous growths is a warning of the imminence of sludge bulking.

Oxygen requirements vary according to the characteristics of the incoming sewage and to a lesser extent, according to the condition of the activated sludge. At least one part per million of dissolved

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* For a complete discussion of the micro-organisms found in activated sludge and their functions see J. B. Lackey's chapter, "Stream Microbiology," in the author's *Stream Sanitation.*

oxygen should be present in all parts of the aerating tanks. The oxygen demand is greater at the inlet end of the tanks, where the return sludge is introduced, and tapers off toward the outlet. Air supply may be adjusted to meet this tapered demand.

The activated sludge must be removed promptly and continuously from the final sedimentation tanks to avoid oxygen depletion and consequent harm to the living material. In the larger plants this *return sludge* is transported in open channels provided with air diffuser plates to supply oxygen during the trip back to the inlet of the aeration tanks.

Activated sludge is the result of continuous growth whereby much of the organic matter of the incoming sewage is converted into living matter. Hence there is always some *excess sludge* to be disposed of. It may be taken to the inlet of the primary sedimentation tanks for sedimentation and final disposal with the primary sludge, or it may be pumped directly to the sludge disposal unit.

THE INTERMITTENT SAND FILTER

The earliest work of the world-famous Lawrence Experiment Station of the Massachusetts State Board of Health had to do with the treatment of sewage on beds of sand. The sand was of various degrees of fineness and beds of various depths. Application of sewage (without preliminary treatment except for coarse screening) was at rates of the order of 0.1 million gallons per acre per day, in one daily dose. This amounted to a 4-inch depth over the filter area. The sewage disappeared within the body of the bed within a few hours, and, as it drained into the lower strata, air was drawn in through the surface. This intermittent operation, with induced respiration between doses, was recognized as the essential requirement.

The system gained considerable popularity in the smaller Massachusetts towns and elsewhere, but land limitations were too strict to permit its adoption by the cities. It is still a highly satisfactory treatment for the sewage of towns and of institutions in the country. Where land is available, it offers a maximum of service at a minimum of initial and operational cost and of supervision. It is also employed as a finishing treatment, under which designation, design and operating details are discussed (p. 593).

EFFICIENCIES, ADVANTAGES AND LIMITATIONS OF COMPLETE TREATMENT

Complete treatment of sewage by biochemical processes (contact with the biota of activated sludge or filter slimes) may be relied upon for substantial removals of the total organic load. If efficiencies are expressed in terms of the BOD, the trickling filter will oxidize 80 to 90 per cent of the applied load, and the activated sludge treatment, 90 to 95 per cent. Lower efficiencies, if sufficient for local needs, can be had in each system by shortening the period of contact. The intermittent sand filter can be made to yield almost complete purification.

Bacterial reductions, without chlorination, run somewhat parallel. With chlorination, they are greatly aided by the reduction in the chlorine demand accompanying high BOD reduction and can be carried to almost any desired degree of completeness. There is no known substitute for the biochemical processes where high efficiencies in BOD removal are needed to meet stream requirements. For high bacterial efficiencies chlorination of these effluents is usually a more economical procedure than chlorination of the effluents of primary treatments.

First costs of complete treatments works are high. Cost of operation of the activated sludge process is generally the highest of any type of treatment because of the large quantities of air which must be supplied and the expense entailed in disposing of the large volumes of sludge produced. Some of the larger plants have attempted to defray part of this cost by sale of sludge as a fertilizer. The activated sludge process requires highly skilled supervision and is sensitive to variations in the character of the waste treated. It is not economical in small installations.

Trickling filter operations are less expensive than activated sludge, but, unless there is an adequate natural head, pumping costs are higher by reason of the greater head loss. Trickling filter installations can successfully handle considerable variation in character of waste and are almost automatic in operation. Activated sludge layouts require relatively small area, whereas trickling filter installations involve a large plant site. Activated sludge is strictly aerobic and free of odors, whereas trickling filters are subject to odor and fly nuisance.

Biological systems, as conventionally constructed and operated, have been somewhat inflexible, and advantage cannot be taken of variation in natural stream purification capacity paralleling seasonal changes in river runoff. Modifications of design and operation offer promise of providing more flexibility, which will greatly widen their usefulness. These modifications permit biological systems to operate in a range from intermediate treatment to complete treatment, with efficiencies from 60 to 85 per cent, greatly widening the range of adaptability to varying stream conditions with possibilities of reduction in cost over conventional practice.

INTERMEDIATE TREATMENT

Definitions and Principles. Intermediate treatment, as we have defined it, is any system which removes colloidal in addition to suspended organic matter, but falls short of removing dissolved organic matter. It provides a very flexible type of treatment, economically adaptable, in many instances, to seasonal variations in stream requirements.

The basic principles of treatment (chemical coagulation and biological action) are capable of removing colloidal pollution. Chemical coagulation is incapable of removing organic matter beyond the colloidal state. Biological action can accomplish the removal of both colloids and dissolved matter. When employed for the removal of colloids only, it becomes intermediate treatment. This is a relatively new development in the art of treatment, which greatly broadens the possibilities of attaining intermediate efficiencies. The choice between chemical coagulation and biological process, as an intermediate treatment, depends upon various factors. In general, chemical coagulation is preferred where the highest seasonal treatment does not require efficiencies beyond 60 or 75 per cent and where, during other periods of the year, lower removals, approaching primary treatment, are adequate. The biological system is preferred where the entire range of treatment is at a somewhat higher level, with the highest requirements approaching complete treatment and where, during other periods of the year, removals of approximately 60 per cent are sufficient.

CHEMICAL COAGULATION

The combination of principles employed and the arrangement of operating units involved in chemical coagulation treatment, are shown in the typical flow diagrams, Figures 117 and 118. The raw sewage, after passing through the comminutor or screens and shredder, enters the flash mixer and is intimately mixed with the coagulant.

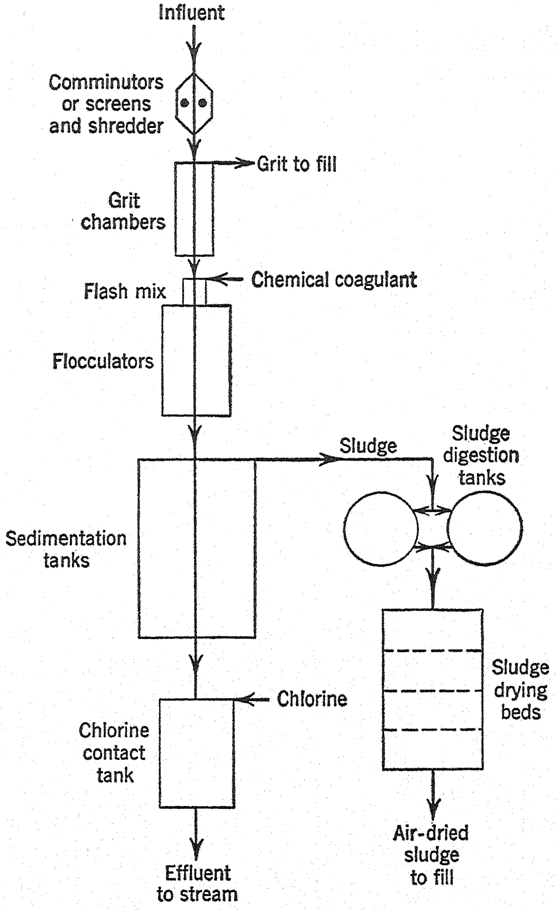
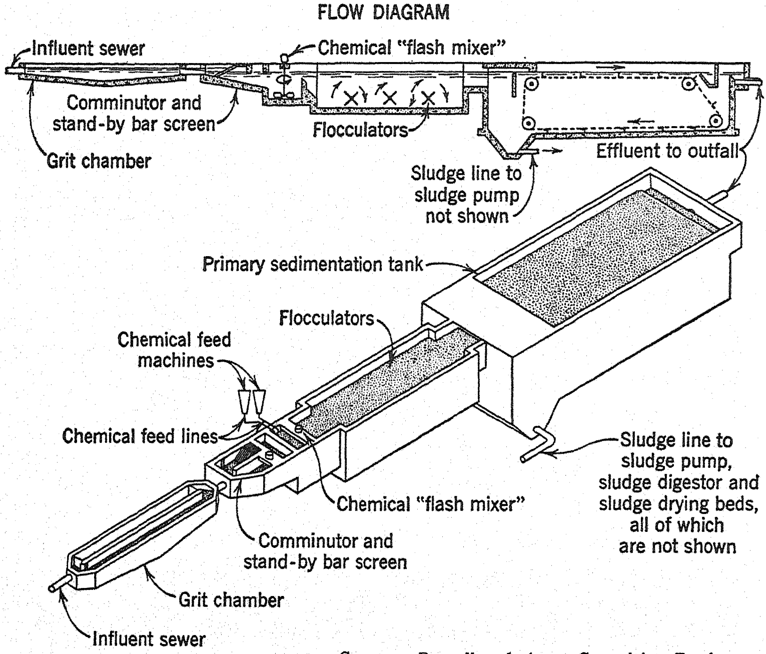


FIG. 117. Schematic flow diagram, intermediate treatment, chemical coagulation.

It then passes to the flocculating chambers where the floc particles are swept through the sewage and pick up the colloids (chemical coagulation principle). The flocculating basins discharge directly into sedimentation basins where the suspended matter and the floc containing the colloids settle out, leaving a clear effluent (hydraulic separation). If bacterial removal is required, the effluent, freed of suspended and colloidal matter, is passed to a contact basin where chlorine is added (disinfection principle), prior to discharge to the receiving stream.

Units. Coagulation units are similar to those employed in water treatment (p. 511). Flash mix is designed to provide a 1- to 2-minute detention and is equipped with a mechanical agitation device or air diffusers for intimately mixing the coagulant with the incoming waste flow. If a Parshall flume is employed to control the flow in the grit chambers, an excellent rapid mix is afforded at the hydraulic jump following the flume, and coagulant can be added here instead of providing the flash mix units. Coagulant feed devices of dry or solution type, similar to those described for water treatment (p. 512), are housed in an operating building and the coagulant piped to the point of application at the flash mix.



Courtesy Russell and Axon, Consulting Engineers

Fig. 118. Chemical coagulation system.

Flocculator basins are designed for 20 to 40 minutes detention period, based on average daily design flow. The basins are either equipped with transverse or longitudinal paddle wheel flocculators or provided with air diffusers as the means for sweeping the floc through the sewage.

The layout should permit by-passing the coagulating units directly from the grit chambers to the sedimentation basins. This will provide flexibility in operation and permit the plant to function as a primary treatment system without coagulation, when stream flow permits.

Sedimentation units and chlorine contact chambers with arrangements for prechlorination are designed similar to those employed in primary treatment.

OPERATION. The major operating problem is the control of coagulation which requires constant skilled supervision. As with water treatment, the coagulant dose must be varied in proportion to the flow of waste through the plant and according to the changing characteristics of the sewage. Where industrial wastes are included with municipal sewage, *p*H adjustments with lime or acid to optimum reactions improve coagulation, with an over-all saving in chemicals. Regulated admissions of industrial wastes of acid and alkaline reaction will effect neutralization and, in fact, can serve as an aid to coagulation. This may involve the construction of temporary storage tanks at the site of the industries in order to regulate the discharge of the wastes to the sewerage system.

Generally, the iron coagulants produce the best results, but under some conditions alum is preferable. As with water treatment, selection of the proper coagulant and necessary dose will be determined by laboratory bench jar tests.

The operation of other units, screens, grit chambers, chlorine contact tanks, and chlorinators, is similar to that described for primary treatment. Sludge disposal control is somewhat more complicated, by virtue of chemical coagulants and the incident *p*H adjustments (p. 610).

The problem of coordinating treatment with stream requirements may necessitate seasonal adjustments in the degree of treatment applied. In the warm low-runoff season, oxygen resources of the stream are at a minimum* and greater reductions in pollution

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* In instances where the stream is closed to reaeration by ice cover and runoff is simultaneously low, a critical condition may also occur in winter.

load are required. During the cold weather months it may even be feasible to by-pass the coagulation units entirely and to operate simply as a primary plant; or flexibility is possible through adjustment of coagulant dose. This feature serves a useful purpose in situations where bathing beach protection is a primary objective.

This type of operation is concerned, not only with the control of quality of the effluent, but also with evaluating the effect of the effluent after it is incorporated as part of the watercourse. Observations of the D.O. and BOD of the receiving stream and its runoff become a necessary part of control, and, by correlating river conditions with treatment plant performance, an operating schedule defining degrees of treatment required for different periods of the year can be established. Such plant–stream operations control directs attention to the real objective of treatment and takes full advantage of self-purification capacity of the natural watercourse, with substantial savings in the cost of treatment.*

BIOLOGICAL INTERMEDIATE TREATMENT

The biological principle in intermediate as in complete treatment can be employed in two ways. One involves passing the sewage through a stationary biological bed, high-rate trickling filters; the other, passing the zoogloea through the sewage, partial aeration (modified activated sludge).

Principles and Flow Diagram. High-rate trickling filters are a recent modification in the conventional practice, greatly extending the flexibility and range of usefulness of trickling filters. The same basic biological principles apply to high-rate filters as to the conventional low-rate beds, but the higher rate of dosing requires certain changes in design and operation. Sewage is applied to these filters at surface rates some 10 times those employed on standard rate filters, that is from 20 to 30 mgad. In order to maintain such high rates it is necessary to apply the sewage continuously by means of rotary arm distributors.

In addition to increased rates of daily load, flexibility in operation is afforded in the provision for recirculation or two-stage series operation (Figure 119).

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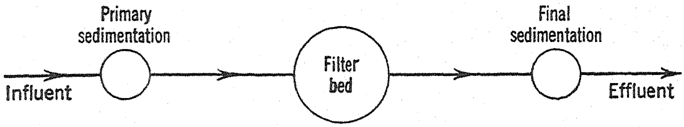
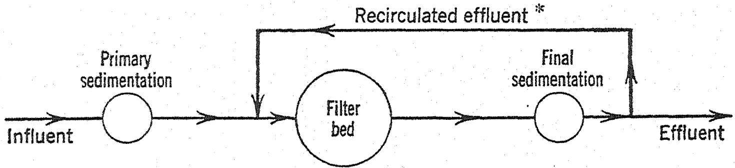
* This type of operation is employed on the Raritan River in New Jersey and the Mississippi River at Minneapolis–St. Paul, Minn.

Design Factors. The sedimentation units are designed similarly to those employed in the conventional trickling filter system, with 2 hours nominal detention for preliminary and 1 to 1.5 hours for final tanks. Where recirculation is practiced, the capacity of sedimentation units must be increased to provide for both the incoming sewage and the recirculated flow. Recirculation ratios (volume of returned sewage divided by volume of raw sewage influent) range from 1 to 3, depending upon the efficiency desired.

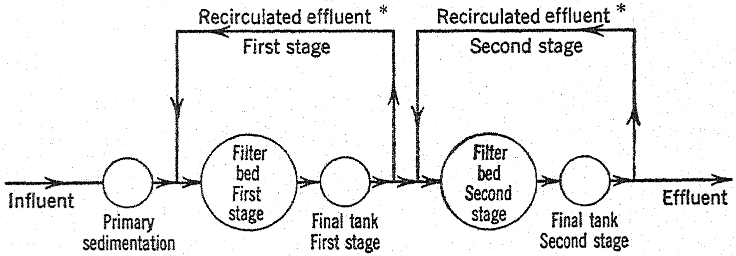


A. Single-Stage Flow Diagram



* Various combinations of recirculation are employed, final tank effluent returned to filter influent or filter effluent returned to primary tank influent or a combination of both.

B. Single-Stage Flow Diagram with Recirculation



* Various combinations of recirculation are employed, and in some instances the final sedimentation tank of the first stage is omitted.

C. Two-Stage Flow Diagram with Recirculation

Fig. 119. High-rate trickling filter flow diagrams.

The filter units are usually circular with rotary distributors and are similar in construction to the conventional beds.

The same principle governing performance of conventional filters (p. 562) applies to the high-rate beds, namely,

$$\frac{L_D}{L} = 10^{-kD}$$

Observations at 2-foot intervals in an 8-foot experimental bed at Englewood, N. J.,* continuously dosed at a hydraulic rate of approximately 20 mgad, indicated an extraction of BOD in successive 2-foot intervals of 50 per cent of that removed in the preceding interval. With these data and the reported operating results of high-rate installations,† k the logarithmic rate of extraction and L the removable BOD fraction are estimated at 0.1505 and 0.784, respectively, as compared with 0.175 and 0.90 for conventional low-rate beds (p. 564). These values are subject to refinement as more data become available, but may be employed to represent average performance of high-rate continuously dosed beds.

As heretofore, L is the quantity removable through the combined performance of the filter and the final sedimentation tank, expressed in terms of the BOD of the applied load in the incoming settled sewage excluding the BOD of any recirculated flow.

Using these values of k and L, Figure 120 is a graphic representation of expected performance. Curve A and the left-hand scale represent the per cent of the removable fraction of the BOD remaining after passage through filter depth D. If the flow passes through a second depth D, or passes a second time through the same filter (recirculation), the value of L_D expresses the ratio of the work done during that second passage to the work done during the first.

Thus, in a 4-foot filter, L_D is 0.25; the work done (removal) has been 0.75. In a second passage the work done would be

$$0.25 \times 0.75 = 0.1875$$

and the total work in two passages,

$$0.75 + 0.1875 = 0.9375$$

leaving

$$0.0625 \quad \text{or} \quad 6.25 \text{ per cent}$$

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* L. W. Morrill and H. T. Ell, Bur. Eng., New Jersey State Dept. Health, 1939.

† G. Walton, Upper Mississippi River Basin Sanitation Agreement, March 1943.

National Research Council, Subcommittee on Sewage Treatment of the Committee on Sanitary Engineering, *Sewage Works J.*, **18**, 791, 1946.

F. W. Mohlman, *Sewage Works J.*, **8**, 904, 1936.

the indicated value at a depth of 8 feet. In general, we have

	Removed	Remaining
1st passage	$1 - L_D$	L_D
2nd passage	$L_D(1 - L_D)$	$L_D - L_D(1 - L_D)$
Both passages	$1 - L_D^2$	L_D^2

and so on for successive passages.

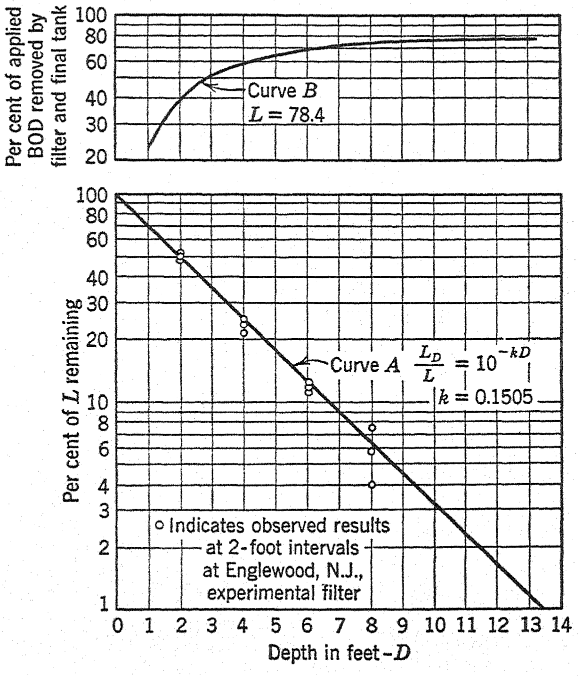

FIG. 120. Relation between bed depth and performance of high-rate trickling filters, continuous application. 25 to 30 mgad.

Figure 121, based upon Figure 120, shows the performance to be expected of filters of various depths, with loadings and removals expressed in pounds of 5-day BOD of settled sewage (exclusive of BOD contained in any recirculated flow) applied per day per unit surface area of bed.

The previous discussion of the limit of BOD loading and its relation to the removable fraction L (p. 563) applies to high-rate beds. Performance of high-rate beds over a wide range of loading per unit of bed area confirms the previous finding that L, and, therefore, the fractional removal for a bed of any given depth, remains constant up to the limiting loading. The limit appears to be in the vicinity of 1 pound of 5-day BOD per square foot per day at temperature near 30 degrees centigrade. The equilibrium accumulation of BOD stored in the bed in relation to daily extraction by the bed and the rate of biological oxidation are given by

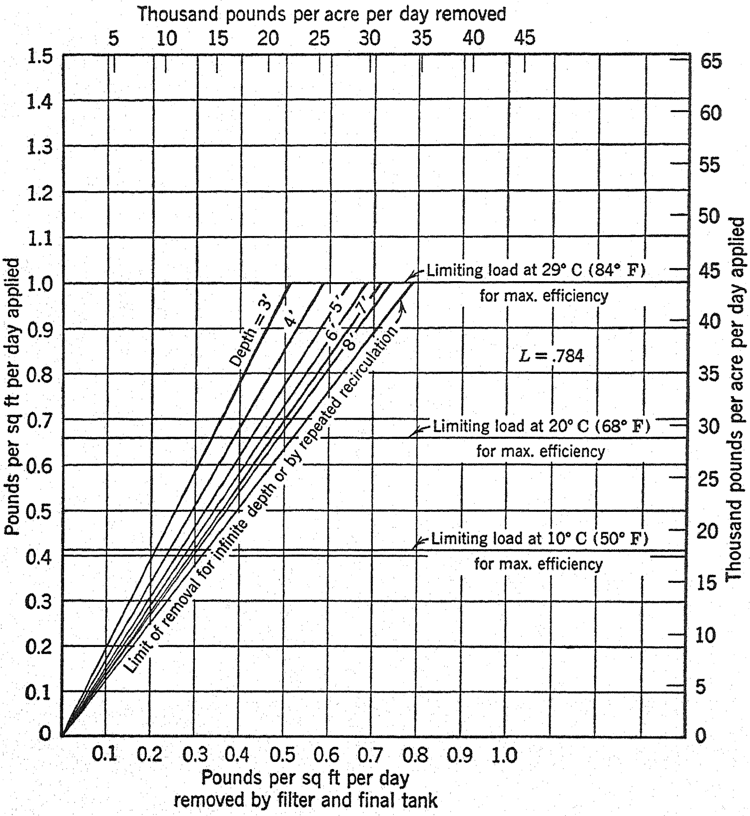

FIG. 121. Relation between loading and removal by high-rate trickling filter and its final sedimentation tank, in terms of pounds of 5-day *BOD* of settled sewage (exclusive of *BOD* of any recirculated flow).

$$L_e = \frac{L_p}{2.3k_1}$$

in which L_e represents the accumulation of BOD within the bed, L_p the daily extraction by the bed, and k_1 the logarithmic rate of biological oxidation (p. 309) at the particular temperature involved. At a temperature of 29 degrees centigrade, $k_1 = 0.15$, and with an applied load of 1 pound per square foot per day, the maximum removal L would be 0.784 pound per square foot per day (Figure 121); and L_e the maximum accumulation would be

$$L_e = \frac{0.784}{2.3 \times 0.15} = 2.26 \text{ pounds per square foot}$$

This applies to a bed of infinite depth; the accumulation for beds of other depths will be proportional to their respective extractions.

Since a time element is involved in building up to the equilibrium accumulation (99 per cent reached in approximately 13, 20, and 32 days at 29, 20, and 10 degrees centigrade, respectively), hourly and daily variations for short periods in excess of the limiting load as an average may be applied without material increase in accumulation, and therefore, without appreciable loss of efficiency. This stabilizing influence of bed accumulation serves as a shock absorber to sudden changes in load and is one of the most valuable characteristics of all trickling filters.

If, at 29 degrees centigrade, 2.26 pounds per square foot represents the maximum allowable accumulation of BOD without a decrease in L and efficiency, it is obvious that, as temperature drops and the biological rate of oxidation k_1 diminishes, the daily removal, and hence the daily applied load, must be reduced in accordance with

$$L_p = 2.26 \times 2.3 \times k_T$$
$$(k_T = k_{20} \times 1.047^{T-20})$$

Hence, to preserve maximum efficiency with maximum daily loading it is necessary to reduce the daily applied load from 1.0 pound per square foot at 29 degrees centigrade to 0.66 pound at 20 degrees and 0.42 pound at 10 degrees. These limits are identical for loadings of filters of all depths and are designated on Figure 121.

Although efficiency remains constant at its maximum for BOD loadings below the limiting load, data are insufficient at this time to determine the exact nature of the decline in efficiency under excess loading. It appears that for normal biological oxidation of sewage the maximum removal at equilibrium accumulation remains constant with excess loadings to a limited extent, ultimately followed by a rapid decline to complete breakdown. This implies that, when the maximum removal is reached, any increment of excess loading applied simply passes through the bed. The efficiency for any depth and temperature at excess loading, therefore, is the ratio of the maximum BOD removal (at the specified depth and temperature) to the total applied load. Thus, for a 3-foot bed at 29 degrees centigrade maximum removal is 0.508 pound per square foot at an applied load of 1.0 pound per square foot, or maximum efficiency of 50.8 per cent; at a loading of 1.3 pounds per square foot at the same temperature efficiency would decrease to 0.508/1.3 or 39.1 per cent. Similarly, if the temperature dropped to 10 degrees centigrade, the maximum removal for the 3-foot bed would be 0.214 pound per square foot at a loading of 0.42 pound per square foot, or 50.8 per cent efficiency, but, if the load were 1.3 pounds per square foot, efficiency would decrease to 0.214/1.3 or 16.5 per cent.

Recirculation or two-stage series treatment can be evaluated readily in terms of removal through successive depths (Figure 120). Recirculation is usually expressed as R/I, the ratio of the volume of recirculated flow R to the volume of influent to the plant I. Thus an R/I of 1.0 is equivalent to passing the influent I through the filter twice, which is tantamount to passing I once through two such successive depth intervals. An R/I of 1.5 is equivalent to passing I through twice and 0.5 of I through 3 times. Similarly, if the filters are of the same depth, two-stage series treatment and any recirculation in the second stage are equivalent to additional passages by recirculation through the first stage. The limit of removal by repeated or successive passages by recirculation or series treatment on filters of the same depth is the total removable fraction L.* From Figure 121 it is evident that where deep filters, 6 to 8 feet, are employed, recirculation or series treatment can produce but small additional removals over that of a single pass; but for shallow filters, 3 feet, there is a substantial increment to be obtained. Since all depths are bound by the same limit L, decisions as to the adoption of recirculation or series treatment are guided primarily by economic considerations.

As an illustration of these principles, let it be assumed that, in order to meet stream requirements, a raw sewage flow of 4 mgd carrying a 5-day BOD of 215 ppm must be treated to produce an

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* Recirculation and series treatment, however, are effective only up to the limit at which the total rate of extraction is at or below that producing the maximum allowable accumulation, L_s, for a given depth of bed.

effluent which will not carry more than 1325 pounds of BOD per day during the summer nor more than 2900 pounds during the winter. The summer and winter temperatures are 29 and 10 degrees centigrade, respectively. The hydraulic loading is not to exceed 30 mgad without recirculation, and the primary treatment is expected to remove 30 per cent of the BOD load.

The applied load to the filter amounts to

$$4 \times 215 \times 8.34 \times 0.7 = 5000 \text{ pounds per day}$$

The summer requirements call for a reduction of this load to 1325 pounds, a reduction of 73.5 per cent. This requires an 8-foot bed (Figure 120*B*) with a maximum allowable loading of 1.0 pound per square foot (Figure 121, temperature 29 degrees), or a total area of 5000 square feet. The minimum area compatible with the assigned conditions of hydraulic loading, 30 mgad, however, is 4/30 acre or 5820 square feet, and, therefore, the hydraulic loading factor is controlling and the BOD loading becomes

$$5000/5820 = 0.86$$

Before this value is adopted, however, the cold weather conditions must be investigated.

During cold weather the temperature of the sewage is 10 degrees centigrade, and the stream will accept 2900 pounds of 5-day BOD per day. This calls for a reduction of only 42 per cent of the BOD of the settled sewage by the filter and secondary sedimentation tank.

At 10 degrees centigrade the limiting loading for maximum efficiency (73.5 per cent) is only 0.420 pound per square foot (Figure 121), and the removal at that loading,

$$0.735 \times 0.420 = 0.309 \text{ pound per square foot}$$

If, in accordance with the principles previously discussed (p. 587) this value 0.309 be considered fixed, under conditions of overloading, and if it now be taken to represent 42 per cent of the total applied load, the latter becomes

$$0.309/0.42 = 0.735 \text{ pound per square foot}$$

the corresponding area,

$$5000/0.735 = 6800 \text{ square feet}$$

and the hydraulic rate,

$$\frac{4 \times 43{,}560}{6800} = 25.6 \text{ mgad}$$

As this is within the allowable rate of 30 mgad, the winter conditions are controlling in this situation, and the area 6800 square feet is adopted as a *minimum* value which may be adjusted upward for such items as factor of safety and growth of the community.

Under the design criteria postulated in this example, winter conditions were found to be controlling. If, however, winter removal requirements had been less than 31 per cent, then the winter loading indicated would have been about 1 pound per square foot, and summer requirements would have controlled the filter area required.

As an illustration of recirculation let it be stipulated that recirculation is to be employed during the summer and not during the winter. The 8-foot depth required to meet the required 73.5 per cent summer efficiency is equivalent to successive passages through two 4-foot beds or to two passages through a single 4-foot bed. Such a bed, therefore, with a recirculation ratio of unity would meet the summer requirements, as would various other combinations of bed depth, area, and recirculation ratio.

If a 4-foot bed is selected for a trial design, the following data will be developed.

Summer requirements with recirculation		5-day BOD Pounds per day
Specified removal (0.735 × 5000)		3675
Removal, first pass (Figure 120*B*, 0.588 × 5000)		2940
Removal, second pass (Figure 120*A*, 0.25 × 2940)		735
Total removal (recirculation ratio 1.0)		3675
Allowable extraction 4-ft bed (Figure 121)	0.588 lb. per sq. ft.	
Allowable loading with R/I of 1, 0.588/0.735	0.8 lb. per sq. ft.	
Required area, BOD basis (5000/0.8)	6250 sq. ft.	
Hydraulic loading including recirculation (8/0.1433)	55.8 mgad	
This in excess of 30 mgad limit, hence:		
Required area, hydraulic basis (8/30)	0.2667 acre	
	11,620 sq. ft.	
BOD loading (5000/11,620)	0.430 lb. per sq. ft.	

Check for winter conditions	Lb. per sq. ft.
Maximum removal at maximum efficiency (Figure 121)	0.247
Allowable loading for maximum efficiency (Figure 121)	0.420
Actual loading (as above)	0.430

Winter operation is at slight excess loading, and efficiency is (0.247/0.43) = 57.4 per cent, as against required for winter conditions, 42.0 per cent.

Therefore, 11,620 square feet of 4-foot bed with a recirculation ratio during summer of 1.0 is necessary to meet summer stream requirements, and this bed without recirculation will meet winter requirements with a margin of excess efficiency.

By the same procedure, if a 5-foot bed is selected, the recirculation ratio may be reduced to 0.788 and the area to 10,380 square feet with winter efficiency without recirculation at 56.3 per cent; and, for a 6-foot bed, recirculation ratio may be reduced to 0.571 and the area to 9120 square feet with winter efficiency without recirculation at 52.5 per cent. On the other hand, if a 3-foot bed is selected, the recirculation ratio must be increased to 1.75 and the area to 15,970 square feet, and, since with this area the winter BOD loading is below the limiting load, the maximum efficiency for a 3-foot bed, 50.8 per cent, is maintained throughout the year.

When recirculation is employed, the limit of hydraulic loading is more likely to be reached before that of BOD loading. In design studies it is important to evaluate both bases of loading and particularly to take into account the lowering of the BOD limit with lowered sewage temperatures.

OPERATION. Operation is continuous, without rest periods, at an average 24-hour application of 25, but not to exceed an average of 30 mgad. Instantaneous rates of application during periods of the day will be above and below the average, depending upon the rate at which sewage comes to the plant and the recirculation practice. The rate of application should not fall below 12 mgad, or the beds will not be flushed properly, and distribution over the bed will not be uniform. The high rates of application per unit of bed surface induce continuous sloughing, in contrast to the spasmodic sloughing of conventional low daily rate beds.

Fly nuisance is limited, by virtue of continuous application of sewage, which prevents the emergence of adults. Odor is minimized through dilution of recirculation.

The major advantage of the high-rate trickling filter is its flexibility, with a wide range in efficiency from complete treatment, 80 to 90 per cent, down to intermediate treatment, 60 to 75 per cent over-all removal. Its greatest usefulness lies in the range of intermediate treatment, with recirculation employed on a seasonal basis correlated with varying stream requirements (p. 545).

PARTIAL AERATION. Partial aeration* is a recent modification in the conventional practice of activated sludge which widens its usefulness and offers promise of saving in cost of treatment. Essen-

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* The term partial aeration as used here includes modifications of the activated sludge process referred to as *modified aeration* and *step aeration*.

tially, the same biological principles are employed as in the conventional practice, but the quantity of sludge returned and its time of contact with the sewage in the aeration tanks are substantially reduced (one half to one third). The flow diagram is similar to that for the conventional layout (Figure 115) except that greater flexibility is provided for admitting returned sludge and sewage to the aeration tanks.

Units. Pretreatment units and the final sedimentation tanks are similar to those in the conventional process. Experimental and operating results* are, as yet, too meager for precise determination of load and efficiency limits, but the general characteristics of the load–efficiency curves (Figure 122) indicate a rational basis for design of aerator capacity. Load is expressed in terms of pounds per day of 5-day BOD applied per thousand cubic feet of aerator capacity. Efficiency is measured both in pounds and in per cent removed (aerator plus final sedimentation). Up to an applied load of 60 pounds, the relation appears to be linear as between applied load and total removal with a constant efficiency of about 83 per cent. Beyond this point the efficiency decreases about 5 per cent for each increase of 20 pounds in the applied load. The maximum work appears to be done with an applied load of 200 pounds and removal of 100 pounds (50 per cent removal).

Flexibility in contact period in the aerators is provided by dividing the load among three or more units, or by admitting sewage or return sludge at various points along the aeration channels.

Operation. The major distinction in operation of partial aeration and conventional activated sludge is the low concentration of solids maintained in the mixed liquor of the aeration tanks. Expressed on a dry solids basis, the concentrations range from 200 to 800 parts per million. These low concentrations, combined with short aeration periods, substantially reduce the quantity of air required.

The density of the excess sludge, wasted to the sludge disposal plant, is much greater than in the standard system (3 to 5 per cent solids as compared with 1 to 2 per cent), and its volume is correspondingly less.

The process is sensitive in operation, and hourly variations in load during the day are reflected over a wide range in efficiency,

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* L. R. Setter, W. T. Carpenter, and G. C. Winslow, *Sewage Works J.*, 17, 669, 1945.

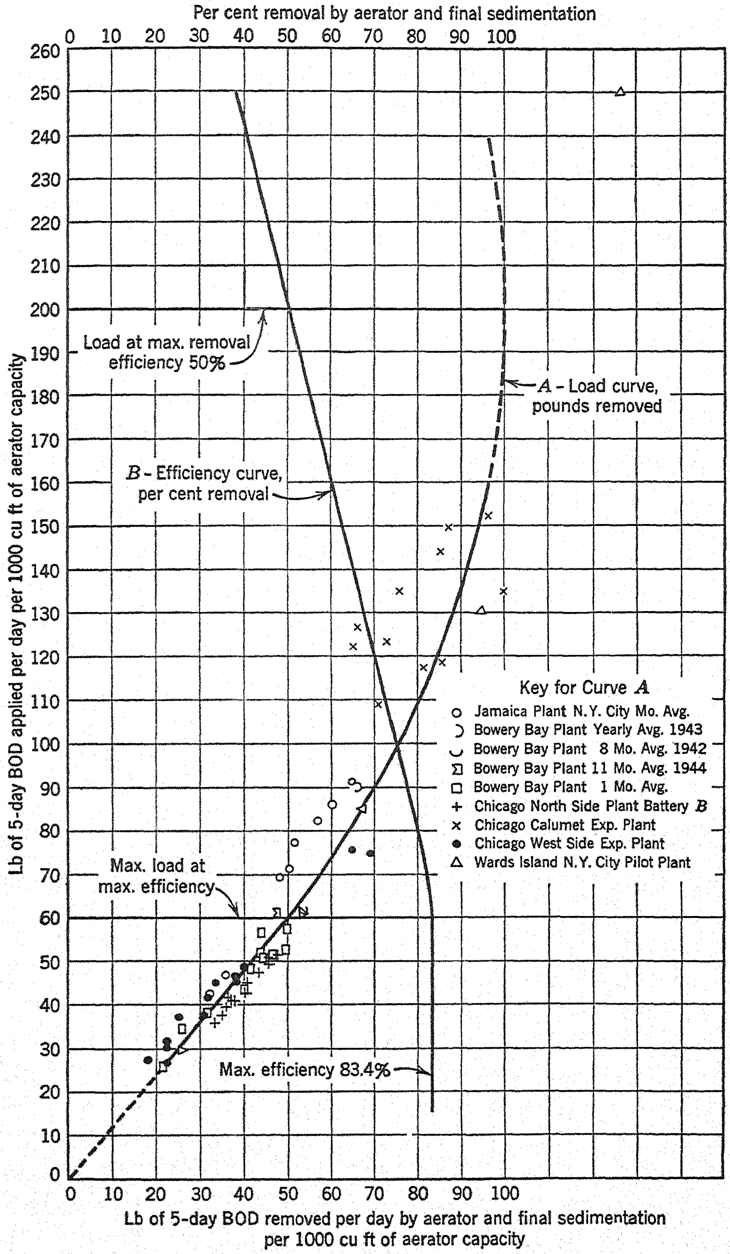

FIG. 122. Relation between applied *BOD* load and removal by partial aeration.

unless compensated by change in aerator contact period. On the other hand, this system responds quickly to variation in contact period with load, with adjustments in terms of hours, as contrasted with the rigidity in operating control of the conventional process, where days may be required to re-establish sludge activity and desired efficiency. The responsiveness of the process under skilled supervision places partial aeration with high-rate trickling filters and chemical coagulation as an intermediate treatment well adapted to varying seasonal and stream requirements.

EFFICIENCIES, ADVANTAGES, AND LIMITATIONS OF INTERMEDIATE TREATMENT

The major advantage of intermediate treatment is the economy resulting from its flexibility in providing a wide range of efficiency. This is particularly true of chemical coagulation. Although a sensitive process, it is responsive to variations in dosage of coagulant and can be readily discontinued and again immediately resumed without the "maturing" stage required of biological systems. Chemical coagulation with high dosage of coagulant can remove practically all colloids and attain efficiencies as high as 75 per cent removal of BOD and, where stream requirements permit, efficiencies can be scaled down simply by reducing the dosage or by-passing the coagulating units and operating as a primary system (30 per cent removal of BOD). However, its sensitivity can be a disadvantage, since it can be thrown out of proper operating balance by sudden shock loads such as might occur in unregulated industrial waste discharges. With continuous skilled supervision, however, uniformity in results can be obtained.

The area required for plant site is small, and no great losses of head are incurred through the process. The cost of construction is lower than in biological systems, but use of chemical coagulants increases operating cost. Odors and other nuisances are satisfactorily controlled under this system.

Intermediate systems using the biological principle (high-rate trickling filters, partial aeration) offer considerable flexibility in efficiency, particularly in the higher ranges. After reaching maturity the biological units must remain in operation in order to maintain the process. Hence, they cannot be by-passed, as in chemical coagulation. They serve best in a range of efficiencies above 60 per cent.

High-rate trickling filters are less sensitive to variations in load than chemical coagulation and do not require constant skilled supervision. Cost of construction is somewhat higher than chemical coagulation, but operating cost may be less. However, substantial head loss takes place through the trickling filter installation, and cost of pumping increases operating expense, especially where recirculation is practiced.

High-rate trickling filters require substantially less area than the conventional low-rate filters, but, in general, more than a chemical coagulation layout.

Partial aeration can be thrown off normal operating balance by sudden variations in load and is extremely sensitive in operating control, requiring continuous skilled supervision. The plant can be constructed on a relatively small area. First costs and operating costs are usually higher than for chemical coagulation and high-rate filters, but, as experience is being gained with use of lower quantities of air, operating expenses may be reduced. Head losses through the plant are small. Flexibility in the upper ranges of efficiency can be obtained by varying the contact time in the aeration chambers, and efficiencies approaching complete treatment are more readily within reach of the process. The sludge produced is bulky and high in water content, which adds to the difficulties and expense of sludge disposal, which, however, are substantially less than with the conventional activated sludge process.

FINISHING TREATMENT

Where a highly purified effluent is required, a finishing treatment is sometimes justified. Not only does this provide a somewhat greater over-all efficiency in the average operation, but, what is more important, it constitutes another barrier or additional factor of safety.

INTERMITTENT SAND FILTRATION. The intermittent sand filter (p. 576) serves this purpose excellently. The beds are made somewhat like those described for water filters. Sand of 0.25 to 0.5 millimeter effective size is laid in beds 2 or 3 feet deep over the usual underdrain system. The liquid is applied over the surface by wooden troughs with spaced side outlets. Application is intermittent, but, when partially treated effluent is being treated, the filter will be sufficiently aerated if dosing is not more frequent than every 4 hours. This permits rates of operation of 400,000 to 800,000 gallons per acre per day when the effluents are received from a complete treatment system.

The low rate of dosage and long rest periods insure aerobic conditions. The accumulation of humus within the bed is slight, and no sloughing occurs. The surface of the bed is raked and harrowed occasionally to break up surface accumulations of debris. In northern climates the beds are furrowed with the approach of winter. The sewage flows along the furrows, and the ridges support the ice covering.

RAPID-SAND FILTRATION. Some designers have employed adaptations of the rapid-sand filter (p. 510) as a finishing treatment. Liquor is passed continuously through a shallow mat (3 inches) of sand or fine magnetite ore, supported on a screen. The high rates of water filtration (125 to 190 mgad) may be employed. At these rates the sand mat requires frequent almost continuous cleaning which is accomplished by a traveling backwashing apparatus. These rapid filters function on the principle of mechanical straining, rather than biological action, and hence are limited to the removal of suspended matter. They serve as leveling devices, insuring greater uniformity in daily output of plant effluent. They do not provide the high degree of finishing treatment afforded by intermittent slow-sand filters. By treating effluents of primary sedimentation or chemical coagulation, over-all efficiency may be increased 10 to 20 per cent in suspended solids removal, 5 to 12 per cent in the removal of BOD.

CHLORINATION, described as a final treatment in most of these combinations, might properly be regarded as a finishing treatment. It serves to reduce the bacterial population of the effluent.

Chlorination functions poorly upon raw sewage. Its power of penetration into solid particles is poor because of the interfering reactions with organic matter. It is necessary that suspended organic matter be in a finely subdivided state in order that chlorination may be effective upon the bacteria contained within its particles. Primary sedimentation, therefore, constitutes a minimum prerequisite for efficient chlorination.

Chlorine becomes more effective with further reduction of the organic matter (chlorine demand) and may be applied as a finishing process to effluents of any combination of treatments to bring about bacterial reductions of practically any required degree.

SLUDGE DISPOSAL

Sludge, the inevitable by-product of sedimentation of polluted waters, consists principally of organic settleable solids deposited as a bulky fluid mass. Hydraulic separation from the line of flow of the treatment process is only the first step in the ultimate disposal of this fraction of the pollution load. Final disposal involves a rather complex chain of treatment operations.

SLUDGE VOLUME

The volume of sludge recovered from unit volume of sewage is determined by the initial concentration of suspended solids, the extent to which they are removable by the processes employed, and the moisture (or dry solids) content of the resultant sludge. The normal per capita contribution of suspended solids in municipal sewage is 0.2 pound per day (dry weight). This quantity, in a spent water supply of 100 gallons per capita, is equivalent to a concentration of 240 parts per million of suspended solids.

The efficiency of removal of suspended solids depends upon the type of treatment process employed and the design of the sedimentation unit. Primary treatment, with 2 hours' detention in well-designed sedimentation units, will remove up to 65 per cent. Chemical coagulation, by coagulating the fine dispersed matter, may remove 85 per cent, and activated sludge, up to 95 per cent.

The moisture content of the sludge likewise varies with the treatment. Primary and chemically coagulated sludges will range between 92 and 97 per cent moisture. Activated sludge is more bulky and its moisture content is variable; it may run from 96 to 99 per cent.

VOLUME VARIATION WITH WATER CONTENT. The moisture content of wet sludge radically influences its volume. If the minor influence of the slightly greater density of the dry solids over that of water is disregarded, the sludge volume per pound of dry solids varies inversely as the dry solids content.* Thus a 98 per cent sludge (2 per

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* The exact relation between sludge volume per pound of dry solids V_{sl}, the per cent of dry solids s, and the density of the solids d is

$$V_{sl} = \frac{1}{8.34}\left(\frac{1}{d} + \frac{100}{s} - 1\right) \text{ gallons}$$

which, at $d = 1$, becomes

$$V_{sl} = \frac{100}{8.34s} \text{ gallons} = \frac{100}{62.5s} \text{ cubic feet} \qquad (1)$$

cent solids) will have twice as much volume, per pound of solids, as a 96 per cent sludge (4 per cent solids). If the dry solids are assumed to have a specific gravity of 1.2, the relation between sludge volume, expressed as gallons per pound of dry solids, and moisture (or dry solids) content of the sludge is shown graphically in Figure 123. It may be seen that one pound of suspended solids (dry weight), removed by primary treatment, as a sludge of 95 per cent moisture content, will produce about 2.4 gallons of sludge; and the same solids, removed during final sedimentation of an activated sludge, 98 per cent moisture, will produce about 6 gallons. Increasing the moisture content of this sludge to 99 per cent will double its volume.

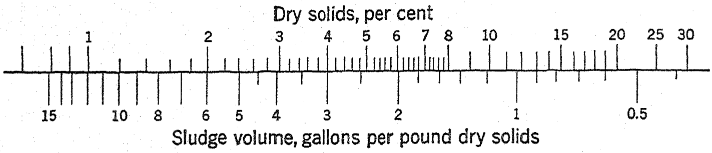


FIG. 123. Variation of sludge volume with water content. Dry solids of specific gravity 1.2.

The quantity of wet sludge to be removed from the line of flow per million gallons of average municipal sewage will range from 3000 to 11,000 gallons, depending upon the treatment process as is indicated in detail in Table 53.

METHODS OF TREATMENT

The purpose of sludge treatment is threefold: stabilization of the organic matter; destruction of pathogenic organisms; dewatering to reduce the volume and facilitate ultimate disposal. Three methods of sludge treatment most frequently employed to satisfy these requirements are biological digestion and partial dewatering, heat drying, and incineration. Sludge digestion utilizes the biological principle of anaerobic decomposition (p. 497) for stabilization and destruction of pathogens, followed by partial dewatering on sludge-drying beds or vacuum filters. In heat drying raw sludge is first partially dewatered, usually by vacuum filtration, and then dried with hot gases, to stabilize the organic matter and destroy pathogens. The dried sludge can be reduced to an inert ash by incineration, the sludge itself serving as fuel.

TABLE 53

PRODUCTION AND CHARACTERISTICS OF SLUDGE. VARIOUS TREATMENT PROCESSES

Treatment	Suspended Solids			Sludge				
	Before Sedimentation Ppm	Removed as Sludge		Water, %	Dry solids		Wet sludge, Gal.	
		%	Ppm		%	Lb per Million Gal. Sewage	Per Lb Dry Solids	Per Million Gal. Sewage
Primary	240	66.5	160	95	5	1330	2.4	3200
Chemical coagulation								
(*a*) Organics (suspended solids)	240	85	204	95	5	1700	2.4	4080
(*b*) Inorganics (floc $Fe(OH)_3$)				95	5	90*	2.4	220
(*c*) Organics + inorganics						1790		4300
Activated sludge (no primary sedimentation)	240	95	228	98	2	1900	6.0	11,400
Activated sludge with primary sedimentation								
(*a*) 1-hr primary sedimentation	240	58	139	95	5	1160	2.4	2780
(*b*) 2-hr final sedimentation	about 100	89	89	98	2	740	6.0	4450
(*c*) Primary + final			228			1900		7230
Trickling filters								
(*a*) 2-hr primary sedimentation	240	66.5	160	95	5	1330	2.4	3200
(*b*) 1-hr final sedimentation following beds				93	7	400†	1.7	680
(*c*) Primary + final						1730		3880

* Theoretical combining weight per grain per gallon of $FeCl_3$ coagulant: 1 lb $FeCl_3$ = 0.6588 lb $Fe(OH)_3$ floc; or for alum coagulant, 1 lb alum = 0.2344 lb $Al(OH)_3$ floc.

† The quantity of humus from the beds will run considerably above 400 lb per mg for short periods during spring and fall sloughing. Also, the quantity of final sludge will be greater for high-rate filters.

DIGESTION AND PARTIAL DEWATERING

Sludge Digestion. The most common method employed for conditioning sludge for safe ultimate disposal is digestion. Figure 124 shows a flow diagram of a typical layout. Raw sludge, withdrawn from the sedimentation units of the treatment works, is pumped daily to digestion tanks (Figure 125). The digestors may be covered to retain odors and, frequently, to recover gas; and they may be heated to maintain optimum conditions for anaerobic decomposition. A 25- to 30-day period of digestion reduces the organic matter to a stable humus of approximately 10 per cent solids. Portions of the digested fluid mass are withdrawn from the bottom of the digestors periodically for partial dewatering on sludge drying beds or vacuum filters.

During the process of digestion liquification and gasification take place, as well as consolidation and reduction of the moisture content of the humus residue. The gas formed is predominantly marsh gas or methane (CH_4), an excellent fuel. It may be utilized to heat water, circulated in coils within the digestor to maintain the temperature, or to heat the daily additions of sludge prior to entering the digestors. In large installations the gas is used in gas engines for power requirements of the treatment plant, and the engine cooling water is used to maintain the temperature of the digestors.

The sludge mass within the digestor tends to stratify, with well-digested humus at the bottom, lighter gas-entrained masses rising to the top, and more or less clear liquid between. The supernatant liquor is tapped from the middle zone and withdrawn daily to make room for the daily additions of fresh sludge. This liquor is discharged to the inlet of the treatment works.

Partial Dewatering. Figure 124 shows two systems commonly employed for partial dewatering: (*a*) *sludge drying beds;* and (*b*) *vacuum filtration.* Climate permitting, drying beds may be uncovered. A common practice is to enclose a portion of the required dewatering area in glass to permit drying operations during rainy seasons. The digested sludge is discharged as a fluid mass on the drying units to a depth of 8 to 12 inches. Within 24 hours, the gravity water contained in the digested sludge drains through the sand and gravel, leaving a shrunken cake on the sand. Further dewatering is accomplished by evaporation, with loss of moisture to the air. Within 2 weeks (summer temperature) this cake, shrunken and cracked into chunks 3 to 4 inches thick, is sufficiently dry to be removed by

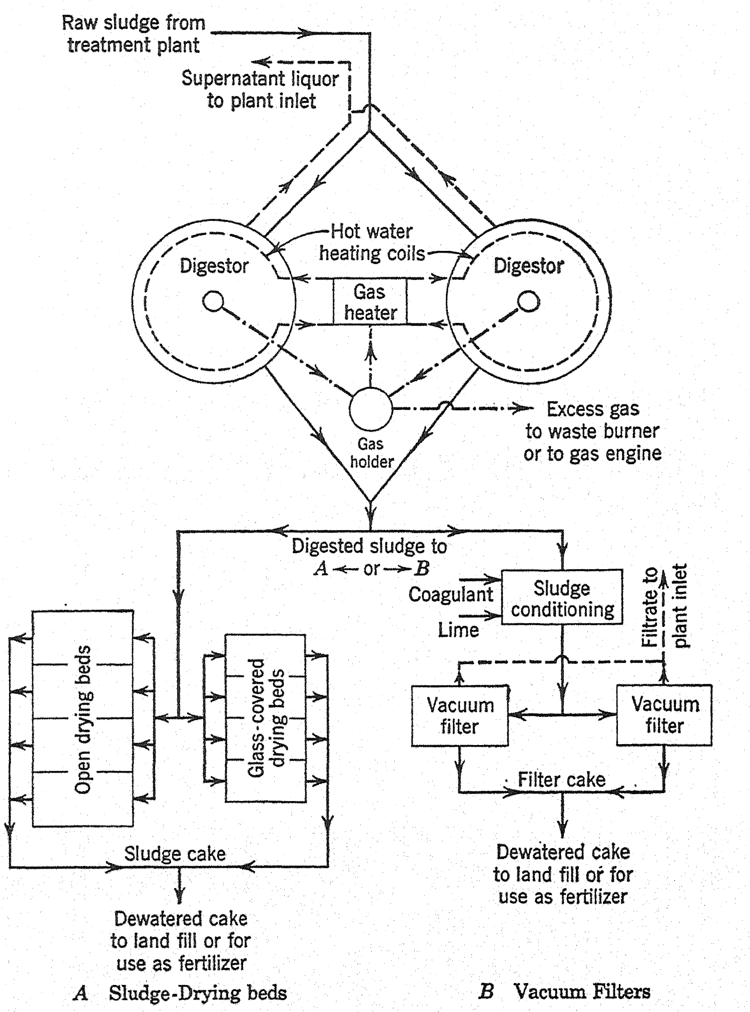
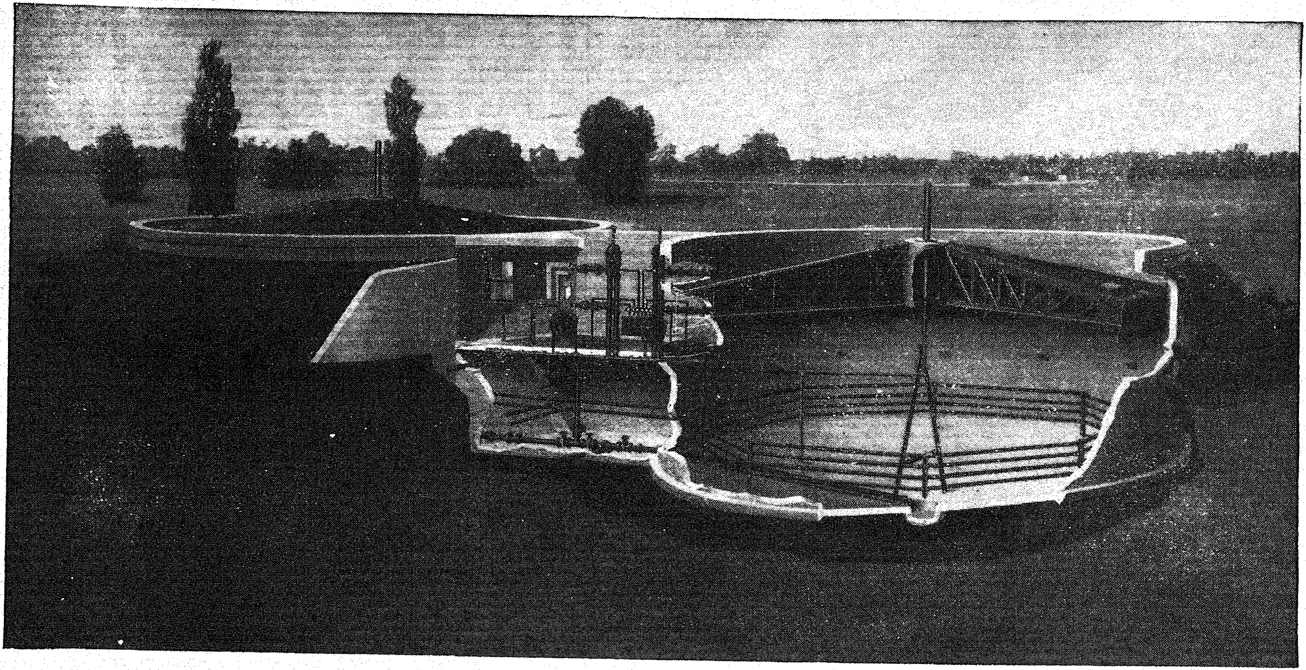


FIG. 124. Sludge treatment.

Digestion and partial dewatering.

forking. The cake, when broken up or shredded, resembles in appearance and odor the humus found in natural forests.

An alternate treatment utilizes the mechanical principle of vacuum filtration (p. 430). The digested sludge is taken to a batch sludge-conditioning unit, into which a coagulant and lime are mixed. The



Courtesy Pacific Flush Tank Co.

FIG. 125. Arrangement for twin digesters (floating-cover type) and control chamber.

conditioned sludge is then fed to a reservoir in which the drum of the vacuum filter revolves partially submerged. The vacuum within the drum dewaters the sludge retained on the filter cloth to a 1/16- to 1/4-inch cake of 70 to 75 per cent moisture content.

DESIGN OF DIGESTION AND DEWATERING UNITS

Capacity. The sludge digestion capacity required is the sludge volume of the total load added during the digestion period, minus losses in volume during digestion (removed as supernatant water) and plus the volume of digested sludge accumulated during the period between withdrawals.

The organic fraction of the sludge, the *volatiles,* ranges from two thirds to three quarters of the dry solids. In turn, only two thirds to three quarters of the volatiles are digestible, as indicated by cessation of gas production. Complete digestion, or practical stabilization suitable for disposal without nuisance, is achieved as the end point of gasification is approached (90 per cent of ultimate gas production), and at this point about 75 per cent of the volatile fraction has been destroyed. The residue of complete digestion, therefore, comprises the nonorganic fraction of the dry solids plus the nondigestible portion of the organic fraction or in all about one-half the total solids.

The period of digestion required to bring about this stabilization depends upon the temperature of digestion. Under controlled heating, with the sludge maintained at 85 to 95 degrees Fahrenheit, digestion is completed in about 25 days, but, for practical design, an allowance of 30 days is recommended. For unheated tanks in mild climates where the monthly average temperature does not fall below 60 degrees Fahrenheit, digestion is completed in about 55 days, with practical designs, however, based on 60 days. In severe climates where sludge temperature falls below 50 degrees Fahrenheit, digestion practically ceases, and therefore, 60 to 90 days of dead storage for undigested sludge is provided in addition to the normal unheated digestor capacity.

In freezing weather sludge cannot be withdrawn for dewatering on drying beds, and, consequently, even where digestors are heated, dead storage of 60 to 90 days is provided, but in this case for completely digested sludge. Such storage is not required where vacuum filters or heat drying is employed.

The interval between withdrawals of digested sludge depends upon the method of dewatering employed. With vacuum filtration, sludge may be withdrawn daily; with sludge-drying beds, 10 days to 2 weeks are required for dewatering, and, hence, withdrawals are periodic, with 15-day storage allowance in digestors. Also, in severe climates, 30 to 90 days of dead storage of digested material are provided as a safeguard against inability to dewater on beds.

The water content of the sludge added daily to the digestors varies with the type of treatment. The moisture content of the digested sludge approaches 90 per cent. With these basic design conditions, the capacity of digestors is obtained from the following considerations.

DAILY ADDITIONS AND WITHDRAWALS. We may postulate a streamline displacement of the sludge in the system, each particle being retained for exactly the total period of digestion, say t days. The digestion tank will then contain a total of t days' accumulation of the nondigestible fraction plus a certain residue of the digestible fraction. If the total digestion of the latter during t days amounts to the fraction p, then the average extent of digestion throughout the tank (age 0 to t days) will be somewhat greater than one-half p, owing to the geometric rate of digestion. For example, if the digestion amounts to 75 per cent during t days, the average extent of digestion throughout the tank will be about 46 per cent (instead of 37.5 per cent).*

The postulated streamline flow through the tank is never realized, as there is necessarily some mixing of the tank contents. For this reason, it is best to allow for an average reduction in the tank of about one-half the total reduction in the sludge as withdrawn. Under the condition of continuous addition and withdrawal, if

W_d = pounds of dry solids added per day
F = fraction organic (volatiles)
t = digestion period in days
p = fraction of F digested in t days
S = pounds stored (dry weight)

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* In general, if p is the total fraction digested during the period, the average extent of digestion will be

$$p_a = 1 + \frac{p}{2.3 \log (1 - p)}$$

then

$$S = W_d t - \tfrac{1}{2}(W_d t \cdot pF) = W_d t\,(1 - \tfrac{1}{2}\,pF) \qquad (2)$$

If the minor correction for specific gravity of the solids is neglected, the volume of sludge resulting will be (p. 597):

$$V_{sl}(t) = \frac{S}{62.5\left(\dfrac{s_i + s_e}{2}\right)} \text{ cubic feet} \qquad (3)$$

in which s_i and s_e are the fractional proportions of dry solids in the influent and effluent sludges, respectively.

The condition of continuous addition and withdrawal is sufficiently realized in daily additions and withdrawals, so that this formulation will apply to that case.

DAILY ADDITIONS AND PERIODIC WITHDRAWALS. Under these conditions it may be assumed that the digestion is completed in t days, but that withdrawal of *digested sludge* takes place at intervals of t' days. For example, every 15 days sludge is withdrawn which has been in the tank 30 to 45 days, so that all of it has reached the condition of being *completely digested*. The accumulation for the first t days is given in equation (2). The additional accumulation of digested sludge for t' days will be

$$S_{t'} = W_d t'\,(1 - pF) \text{ pounds (dry weight)} \qquad (4)$$

and the additional storage required, over that given in equation (2),

$$V_{t'} = \frac{S_{t'}}{62.5 s_e} \text{ cubic feet}$$

Example. What is the capacity required for 30-day digestion under the following conditions?

Loading, 1 ton per day (dry weight)	$W_d = 2{,}000$ lb.
Fractional-solids content of influent sludge	$s_i = 0.05$
Volatiles, 67 per cent	$F = 0.67$
Digested in 30 days (fraction of F)	$p = 0.75$
	$t = 30$
Withdrawal of digested sludge, 15 days	$t' = 15$
Fractional solids content of effluent sludge	$s_e = 0.10$

Solution.

$$S_t = 2000 \times 30\left(1 - \frac{0.67 \times 0.75}{2}\right) = 45{,}000$$

$$S_{t'} = 2000 \times 15(1 - 0.67 \times 0.75) = 15{,}000$$

$$V_{sl(t+t')} = \frac{45{,}000}{62.5\left(\frac{0.05 + 0.10}{2}\right)} + \frac{15{,}000}{62.5(0.10)} = 12{,}000 \text{ cubic feet}$$

Digestor capacity requirements for sludge from normal municipal sewage, undergoing primary, intermediate, and complete treatments are shown in Table 54.

Sludge-drying beds comprise a filtering medium of sand and gravel of 12- to 18-inch depth. Gravel, graded from 2 to ¼ inches is placed around 6-inch open-jointed underdrains, spaced at not over 8-foot centers on a graded base. A 6-inch layer of sand is placed on the gravel. The beds are surrounded by concrete retaining walls extending 12 to 18 inches above the sand and are subdivided into units (20 to 40 feet wide by 60 to 80 feet long) by creosoted planking. Sludge is admitted at one end and flows over the sand surface, which is slightly graded to aid in distribution.

The bed area required depends upon climate and quantity of digested sludge to be handled, which varies with the type of treatment, ranging from 1.0 to 2.0 square feet per capita, as shown in Table 55. Where glass enclosures are employed, the bed area may be reduced to 40 per cent of that required for open beds.

The capacity requirements of vacuum filters as an alternate method of partial dewatering are considered under heat drying and incineration (p. 611).

OPERATION OF DIGESTION AND DRYING UNITS

Operation of sludge digestors and drying beds is simple, and, once digestion is established, the process maintains itself with a minimum of attention.

Digestors. Since digestion is a biological process, efficient operation depends upon the maintenance of optimum environmental conditions of *temperature, reaction* (*p*H) and *food supply*. Temperature may be maintained at 80 to 95 degrees Fahrenheit by continuous additions of heat to the digestors. Regulation is automatic by thermostatic control. Without artificial heat the sewage temperature

TABLE 54

DIGESTOR CAPACITY REQUIREMENTS

Type of Treatment Works Raw sludge production as per Table 53	Heated Digestors — 30-Day Digestion Period*			
	Cu Ft per Million Gallons per Day of Normal Municipal Sewage Treated	Cu Ft per Ton per Day of Raw Sludge as Dry Solids	Cu Ft Per Capita	
			Theoretical	Usual Practical Limits
(1)	(2)	(3)	(4)	(5)
Primary				$\frac{3}{4}$ to $1\frac{1}{2}$
1. Daily withdrawal of digested sludge†	6700	10,000	0.67	
2. Periodic withdrawal of digested sludge at ½-month intervals	8000	12,000	0.80	
3. Allowing 2 months winter storage of digested sludge	13,300	20,000	1.33	
Chemical Coagulation				1 to 2
1. Daily withdrawal of digested sludge†				
(*a*) Organics	8500	10,000	0.85	
(*b*) Inorganic floc per grain per gal of $FeCl_3$	600‡		0.06	
			0.91	
2. Periodic withdrawal of digested sludge at ½-month intervals				
(*a*) Organics	10,200	12,000	1.02	
(*b*) Inorganic floc per grain per gal of $FeCl_3$	820‡		0.08	
			1.10	
3. Allowing 2 months winter storage of digested sludge				
(*a*) Organics	17,000	20,000	1.70	
(*b*) Inorganic floc per grain per gal of $FeCl_3$	1,500‡		0.15	
			1.85	
Activated Sludge (without primary sedimentation)				$1\frac{1}{4}$ to 3.0
1. Daily withdrawal of digested sludge†	11,400	12,000	1.14	
2. Periodic withdrawal of digested sludge at ½-month intervals	13,700	14,400	1.37	
3. Allowing 2 months winter storage of digested sludge	20,600	21,600	2.06	
Activated Sludge (with primary sedimentation)				$1\frac{1}{4}$ to 2.0
1. Daily withdrawal of digested sludge†				
(*a*) Primary sludge	5,800	10,000	0.58	
(*b*) Final sludge	4,400	12,000	0.44	
	10,200		1.02	

TABLE 54—(*Continued*)

Type of Treatment Works Raw sludge production as per Table 53 (1)	Heated Digestors — 30-Day Digestion Period			
	Cu Ft per Million Gallons per Day of Normal Municipal Sewage Treated (2)	Cu Ft per Ton per Day of Raw Sludge as Dry Solids (3)	Cu Ft Per Capita	
			Theoretical (4)	Usual Practical Limits (5)
2. Periodic withdrawal of digested sludge at ½-month intervals				
(*a*) Primary sludge	7,000	12,000	0.70	
(*b*) Final sludge	5,300	14,400	0.53	
	12,300		1.23	
3. Allowing 2 months winter storage of digested sludge				
(*a*) Primary sludge	11,600	20,000	1.16	
(*b*) Final sludge	8,000	21,600	0.80	
	19,600		1.96	
Trickling Filters				1 to 2
1. Daily withdrawal of digested sludge†				
(*a*) Primary sludge	6,700	10,000	0.67	
(*b*) Final sludge	1,700	8,500	0.17	
	8,400		0.84	
2. Periodic withdrawal of digested sludge at ½-month intervals				
(*a*) Primary sludge	8,000	12,000	0.80	
(*b*) Final sludge	2,200	11,000	0.22	
	10,200		1.02	
3. Allowing 2 months winter storage of digested sludge				
(*a*) Primary sludge	13,300	20,000	1.33	
(*b*) Final sludge	3,600	18,100	0.36	
	16,900		1.69	

* For unheated digestors the digestion period (t) required is 60 days. Except for storage of fully digested material, digestor capacity of unheated tanks is double that of heated.

† Digested sludge taken at 90 per cent moisture.

‡ Based upon theoretical combining weights (page 461). Floc considered as non-digestible and, therefore, no loss of weight. Water content reduced by consolidation to that of digested sludge, 90 per cent.

TABLE 55

OPEN SLUDGE-DRYING BED CAPACITY REQUIREMENTS FOR DEWATERING DIGESTED SLUDGE

Type of Treatment Works Raw Sludge Production as per Table 53	Annual Production of Digested Sludge, Lb per Year Dry Solids per Million Gallons per Day Normal Sewage	Bed Load,† Lb per Sq Ft per Year	Bed Area, * Sq Ft per Capita
Primary	243,000	24.3	1.0
Chemical coagulation‡	345,000	23.0	1.5
Activated sludge	347,000	17.4	2.0
Trickling filter	316,000	21.0	1.5

* Area for glass enclosed beds 40 per cent of open area.

† Bed load for glass enclosed beds 2.5 times open bed load.

‡ Based upon 2 grains per gal of $FeCl_3$ coagulant dosage.

may average from 50 degrees Fahrenheit or less in the northern states to 64 degrees Fahrenheit in Texas and Florida, during the three coldest months of the year. The maintenance of optimum *p*H (7.0–7.4) is dependent principally upon the rate of feeding, food supply.

The first reaction in the complex chain of anaerobic digestion of organic matter is the production of acids and violent gasification. This is followed by a gradual recession of acid production and, finally, the establishment of alkaline conditions and diminution in gas production. The violence of the acid reactions results in irregular gas production, foaming, and a turbid mixture within the digestor such that clear supernatant liquor cannot be withdrawn. If the objectionable conditions of acid digestion are to be avoided, it is essential that the proportion of fresh raw sludge in the acid stages of digestion be kept small in comparison with the old sludge in the alkaline stages, retained in the digestor.* With the 30-day capacity requirements for digestors (p. 603), this low proportion of fresh to old sludge can be maintained, providing raw sludge is added gradually (daily), temperature is kept high enough to insure con-

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* *Two-stage digestion* is a process wherein digestors operate in series. Fresh sludge is added to the first stage, where major gas production takes place. The partially digested sludge is transferred to the second stage, where digestion is completed. Supernatant is withdrawn from the second or quiescent stage, thus providing good separation.

tinued digestion, and digestors are operated to full capacity and are not depleted by withdrawing too large quantities of digested material.

When a digestor is first placed in operation, the establishment of normal alkaline digestion is aided by *seeding* the tank with well-digested sludge from a neighboring treatment works. Where this is impracticable, alkaline conditions can be developed by gradual feeding of sludge into well-heated digestors and controlling *p*H by addition of lime.

An index of good operation is the steady production of gas, an essential feature if gas is to be utilized for power and heating. Temperature, *p*H, and feeding, therefore, are balanced, by experience, to insure a steady gas yield.

HAZARDS. There are certain dangers, primarily of explosion and asphyxiation, associated with gas production. Sludge gas contains 70 to 80 per cent methane (CH_4) which, when mixed with air, is highly explosive. Usually the digestor is provided with a floating cover and trapped overflow to permit changing levels, as sludge and supernatant are withdrawn, without admittance of air. The greatest danger, both from asphyxiation and explosion, is from a partially depleted tank opened for repair. Continued gas formation may build up asphyxiating concentrations, and admittance of air provides an explosive mixture which can be set off by a spark from a tool, breaking a light globe, or carelessness with matches. Recent designs almost preclude the necessity for ever entering a tank once placed in operation. Entrance to the digestors should never be permitted except under the supervision of an engineer familiar with the hazards and the precautions. Smoking in the vicinity of the digestors should be prohibited at all times. Many safety precautions have been incorporated in the design of digestors and gas handling equipment. A discussion of hazards of digestion tank operation has been prepared by the committee on sewage works practice of the Federation of Sewage Works Associations.*

SLUDGE DRYING BEDS. Operation of uncovered sludge drying beds is largely dependent upon weather conditions, temperature, humidity, and precipitation. The function of the glass enclosure in covered beds is to increase the rate of evaporation by increasing the temperature from sun heating and to protect the drying sludge from

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* Occupational Hazards in the Operation of Sewage Works, *Federation Sewage Works Assocs. Manual of Practice* 1, Champaign, Ill., 1944.

rewetting during rainy periods. Sun heating, to be effective, must be accompanied by proper ventilation to carry away the evaporated water vapor. Windows should be opened inwardly at the bottom along the sides to deflect air currents over the bed, and outlet of the air and water vapor should be through windows opening outwardly along the top center ridge. Too frequently inadequate ventilation results in saturation of the enclosed space with moisture so that drying is completely inhibited.

HEAT DRYING; INCINERATION

Heat drying and incineration, although distinct processes, are usually combined; or they may be separated to the extent that the heat-dried product has a certain use as fertilizer. Figure 126 shows a layout for the combined processes. Raw sludge is pumped daily to a conditioning tank where it is conditioned and filtered through vacuum filters (p. 430). This reduces it from a fluid to a solid cake (approximately 75 per cent moisture content). The filter cake is then subjected to heat drying by either of the two systems illustrated.

In the *flash dryer* layout (Figure 126*A*), filter cake is mixed with previously dried sludge which is then passed to the flash drying unit,* into which hot air is blown. The vapors and dried sludge pass to a cyclone separator (p. 181) where the powdered sludge (10 per cent moisture content) is deposited and withdrawn. A portion of the dried sludge is returned to the mixer; the remainder is bagged as a fertilizer or discharged to an incinerator for complete destruction, serving as a fuel to heat gases for the flash dryer.

The vapors from the cyclone separator pass through a heat exchanger where they are preheated (800 degrees) and then blown into the incinerator, together with preheated air necessary for combustion. The vapors are thus completely deodorized by combustion. Excess hot gases not required for the flash dryer are passed through the heat exchanger before discharge to the atmosphere through a flue or flyash cyclone separator and the stack. The incinerator is equipped with an auxiliary fuel burner to augment or substitute for dried sludge as fuel.

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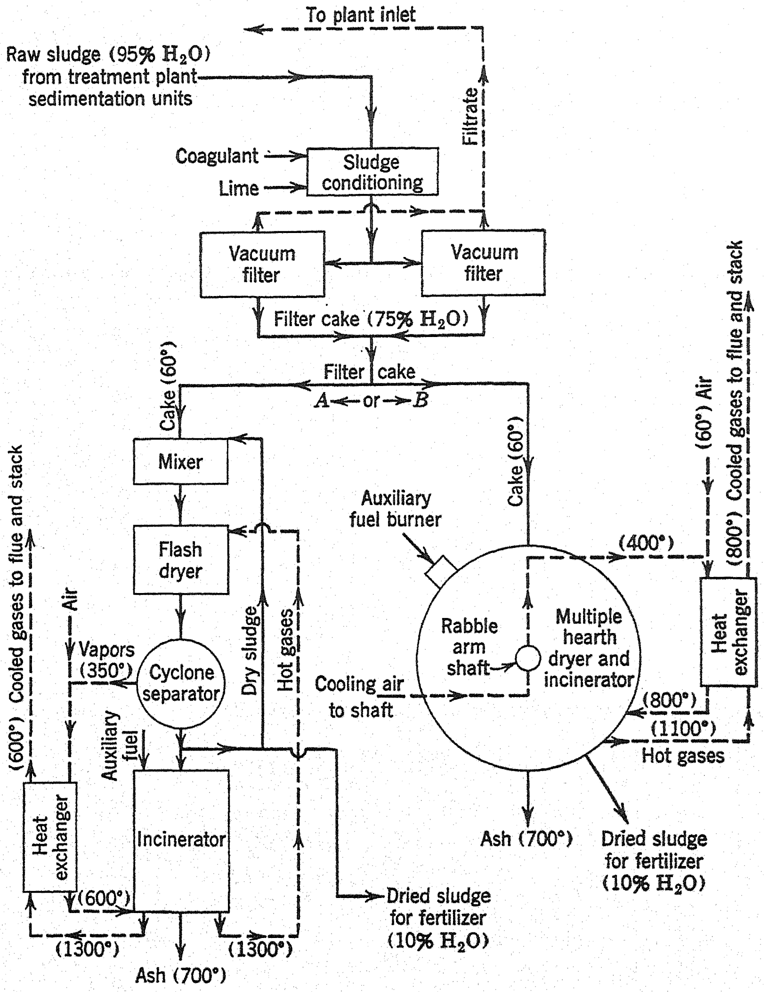
* A flash drying unit developed at the Plainfield Joint Works under the direction of John R. Downes involves spraying digested fluid sludge into a tower into which hot gases are forced. The sludge spray in settling is dried and collected at the bottom of the tower, bagged for fertilizer, or used for fuel in an incinerator to heat air for drying.

In the *multiple hearth* system (Figure 126*B*), the dewatered vacuum filter cake is discharged directly to a vertical cylindrical unit in which both the drying and incineration operations are performed. The unit comprises a series of four or more superimposed and interconnected hearths. Sludge is admitted to the top hearth where drying takes place, incinerated in the central units, and cooled



A Flash Dryer and Incinerator

B Multiple-Hearth Dryer and Incinerator

Fig. 126. Sludge treatment. Heat drying and incineration.

at the bottom hearth, from which ash is removed. A revolving hollow metal central shaft with rabble arms and teeth in each hearth moves the sludge across the successive hearths, alternately inwardly and outwardly, until the ash is discharged at the bottom. The central hearths reach a temperature of 1500 to 1600 degrees Fahrenheit, and cooling air is forced through the central shaft and rabble arms to protect the metal.

The hot gases of combustion are taken off near the top hearth, passed through a heat exchanger, and thence to the atmosphere through a flue and stack. Air used in cooling the central shaft and rabble arms and any additional air required for combustion purposes is forced through the heat exchanger where it is preheated by the outgoing hot gases of combustion to approximately 800 degrees Fahrenheit before delivery to the incinerator. When the fuel value of the sludge is insufficient, additional heat is supplied by auxiliary fuel burners attached to the hearth to maintain a temperature of approximately 1100 degrees Fahrenheit at the combustion outlet to insure complete combustion and deodorization of the volatilized gases.

UNITS. Vacuum filter requirements for partial dewatering of sludge are generally expressed in pounds of filter cake (dry solids basis) per square foot of filter area per hour.* The actual filter area installed is dependent upon an economic balance between capital and operating costs, involving the solids concentration of the sludge, the quantity of conditioning chemicals employed, and the frequency of washing and changing of filter cloth.

Early practice was based on high filter loads, 8 to 10 pounds per square foot per hour, producing a thick cake, ½ to ¾ inches, and a high percentage of conditioning chemicals, 3 to 5 per cent ferric chloride and 10 to 12 per cent lime (percentage dry sludge solids). The recent trend is toward installation of larger filter area, permitting lower loadings, 2 to 4 pounds per square foot per hour, and thinner cake, ⅙ inch to ¼ inch, with consequent savings in conditioning cost and filter cloth maintenance.

A further saving in conditioning chemicals is made possible by installation of sludge thickening devices to reduce the moisture content of sludge prior to conditioning. Substantial savings in chem-

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* Schroepfer suggests an index based upon actual filter area employed per hour, which includes the number of revolutions of the filter drum per hour as well as the area of the drum.

Proc. ASCE, **69**, 41, 1943.

ical costs are also afforded by the elutriation* of sludge, a process of washing out the coagulent-demanding constituents prior to chemical conditioning. The capital and operating costs of these auxiliary devices must be balanced against savings in chemical conditioning. The return of supernatant liquor and elutriation water to the influent of the plant adds to the BOD and solids loads, and may further complicate the treatment of the sewage.

The design requirements of drying and incineration units are involved mechanical engineering problems, the solution of which is based largely upon commercial research and experimentation in the development of practical operating units.

Operation. In contrast to the simple routine operation of sludge digestors and drying beds, those of vacuum filtration, heat drying, and incineration involve constant moment-to-moment skilled supervision. Partial dewatering on vacuum filters requires conditioning of the sludge by coagulation, prior to application to the filters. These coagulation operations involve constant adjustment of coagulant dosage and *p*H adjustment to insure proper dewatering.

The vacuum filters, although automatic, require considerable attention, particularly in the washing and replacing of filter cloth, fouled by impregnation with calcium carbonates and grease. Washings as frequent as every 4 hours permit reduction of coagulants, with increases in filter yield. Filter cloths ultimately become fouled to such an extent that it is more economical to replace them than to compensate for their inefficiency by increasing chemical coagulants. Depending upon comparative cost of chemicals and cloth, replacements are made after 400 to 800 hours of operation.

Heat drying and incineration operations require considerable mechanical attention, despite automatic control. Regulation of the temperature of the combustion chamber, to insure complete stabilization of volatile odors, while preventing overheating of the refractories, is accomplished by balancing air supply, sludge fuel, and auxiliary fuel.

The complexities of vacuum dewatering, heat drying, and incineration preclude their economical application to small installations.

ULTIMATE DISPOSAL

Ultimate disposal of sludge depends upon the treatment it receives. Raw untreated sludge may be barged to sea and dumped at a safe

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* A. L. Genter, *Sewage Works J.*, *6*, 689, 1934.

distance from shore. Digested sludge, partially dewatered, and the ash residue from incineration can safely be disposed of without nuisance as fill for low areas.

Digested or heat-dried sludge may be used as a *fertilizer*.* In addition to its nitrogen, phosphoric acid, and potash content, it serves as an excellent soil builder, by virtue of its organic humus character. Heat-dried sludge is hygienically safe for general use, including garden crops. Digested sludge, partially dewatered, can also be used for garden crops, but it is not recommended for use in contact with vegetables which are to be eaten raw. Although digested sludge has been extensively used under a variety of conditions, no cases of intestinal diseases have ever been reported as traceable to such use. This evidence, however, is inconclusive, and further controlled experiments are necessary to allay all suspicion.

Raw sludge, either liquid or partially dewatered, should not be used as a garden crop fertilizer. It has been employed for forage crops, principally in Europe. If raw sludge is disposed of on the land, it should be plowed under immediately, and the area should be regulated as to use. Modern sludge treatment has advanced to a stage where disposal of raw sludge on the land should not be necessary and should be discouraged.

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CHAPTER 16

RURAL SANITATION

The problem of control of the air, water, and food contacts is no different in the country from in the city. Strictly, there is no *rural sanitation* as such. But the environments differ, as do the problems in relative importance. Many of them also yield to different methods of solution. There is some justification, therefore, in the usual practice of regarding rural conditions as a distinct phase in community sanitation.

At the outset, it is to be noted that rural, in the modern sense, is in no way synonymous with primitive. Rural electrification, the radio, the automobile, and the airplane have shortened time and space and are rapidly blending city and country. Rural sanitation is no longer confined simply to the problems of the individual farm unit. Rather, it embraces all areas, rural, suburban, and even urban districts which are not provided with public health protective services and utilities on an organized community basis. Usually, large cities are unable to keep pace with sewerage, water supply, and other sanitation needs, and there are always fringes of development dependent entirely upon their own initiative, almost to the same extent as the most remote farmer. Beyond the peripheral fringes of the city are numerous hamlets ranging from 100 to 1000 population where no organized effort is made at environmental control, which is left to the individual. Decentralization of industry and public institutions tends to create similar rural sanitation problems. Although the trend of society has been away from rural toward urban living, there is equally a universal urge for the city dweller to travel and vacation in the country. As a consequence, the rural areas are dotted with summer homes or colonies, commercial resorts and recreational areas, children's camps, tourist houses, and cabins. Rural sanitation, therefore, is of vital concern to the city dweller who frequents the country as well as to the farmer, and by virtue of the widespread nature of the problem it carries potentially greater health hazards.

For large areas of the world rural sanitation, unfortunately, has to deal with primitive living under abject poverty and widespread ignorance. Under such conditions even the elementary principle of a definite method of sewage disposal gives place to the promiscuous deposit of human excreta. Although the principles of environmental control are well known, practically, what can be applied is limited by economic considerations and the cooperation of the people. By far the greatest problem is education to the dangers inherent in promiscuous excreta disposal.

The Water Contact—Rural Sewage Disposal

Dr. Leslie L. Lumsden, a student of rural conditions over many years, has said that the problems of rural sanitation are 75 per cent matters of excreta disposal. In certain areas malaria may rank above the remaining 25 per cent, but in general, the estimate is conservative. Remove all concern over excreta, and we remove at one stroke the twin problems of well pollution and of fly-borne and other contamination of milk and other foods. There is also eliminated the dangers from the general dissemination of human excreta over the land and the spread of such diseases as hookworm.

In dealing with *rural sewage disposal* it is convenient to divide the subject matter into water and non-water carriage systems. With the water carriage system the water contact cycle differs from that which has been discussed only in size, not in principle. On the other hand, the more primitive privy (nonwater carriage system) is, perhaps, the only unique feature of rural sewage disposal.

WATER CARRIAGE SEWAGE DISPOSAL SYSTEMS

Where water supply is available, the most satisfactory and convenient method of disposal of sanitary wastes is by a water carriage system. This method affords an easy means of collection and transmission of wastes, but, as with a city sewerage system, it implies a method of *treatment* before return to the water cycle. The degree of treatment to be provided depends, in addition to size of the establishment, upon whether the effluent will be discharged into a surface watercourse or into the ground water by seepage. For the larger installations it may be economically feasible to locate the treatment works adjacent a natural watercourse with the effluent discharging into the stream. In such instances the treatment and disposal problems are no different from those discussed in the preceding chapters. For the smaller establishments it is usually more satisfactory and economical to discharge the effluent from the treatment works into the ground water by subsurface seepage.

QUANTITY

The design of treatment units is dependent upon the quantity of flow, which varies with the type of establishment. Table 56 indicates the usual ranges in volume of sanitary wastes in gallons per capita per day for establishments with modern plumbing and pressure water supply.

TABLE 56

Quantities of Sewage — Rural Water Carriage Sytems

With Pressure Water Supply and Modern Plumbing

Type of Establishment	Average Daily Sewage Flow, Gal. per Capita per Day		
	Minimum	Maximum	Usual Average
Single family residence	25	100+	50
Multiple family residences	35	55	40
Large residences (estates)	70	150+	100
Resort hotels, lodging and boarding houses	50	100	75
Restaurants (toilet and kitchen — per patron)	7	15	10
Resort camps			
Summer (night and day)	25	50	35
Tourist (night only)	15	30	25
Luxury	70	100+	80
Public institutions	75	125	100
Hospitals (including laundry)	150	250+	200
Day schools	15	25	17
Factories (sanitary sewage exclusive of industrial wastes)	15	30	25
Work or construction camps (semipermanent)	35	60	45

DISPOSAL OF THE SOLIDS FRACTION

It will be convenient to consider disposal of rural water carriage wastes as two fractions, the solids and the liquids. The separation of the solids and their satisfactory disposal is usually accomplished by treatment in a *septic tank* (Figure 127) or in an *Imhoff tank*. Both

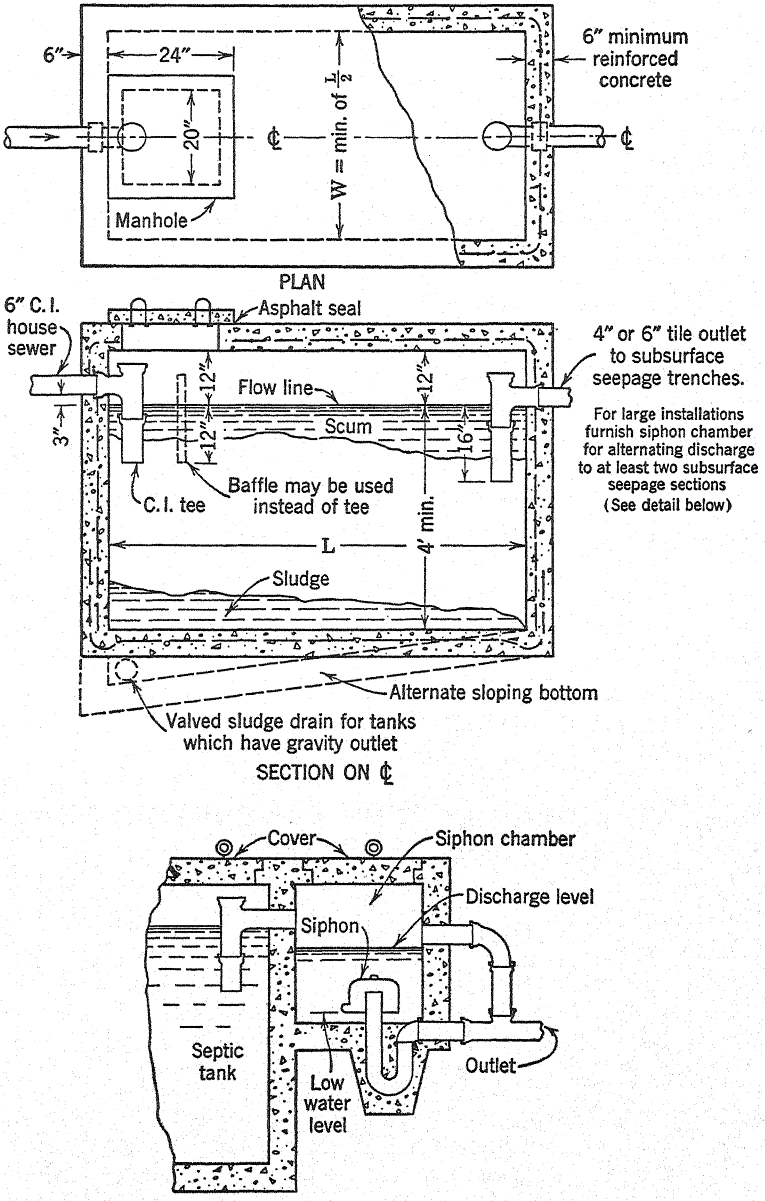

Fig. 127. Typical septic tank.

these devices in the interests of simplicity of operation combine hydraulic separation and digestion in the same unit. The simplicity of construction of the septic tank makes it adaptable to small installations; it is, however, an inefficient unit, as sedimentation and digestion are attempted in the same chamber. Suspended solids are deposited on the bottom, where the processes of biochemical digestion are carried out. Grease* and fats, together with a certain amount of gas-lifted solids from the bottom, collect on the surface as scum. The gasification of digestion is not conducive to good sedimentation.

The Imhoff tank (Figure 110, p. 557) is a distinct improvement over the septic tank, as the sedimentation compartment, although integral with the digestion unit, is so arranged as to minimize the adverse effects of digestion (see p. 600). Imhoff tanks, however, are too complicated in structural detail and too expensive for the small installations.

Capacity requirements for sedimentation and sludge accumulation are generally expressed in terms of hours of nominal detention time, based on the per capita rates outlined in Table 56. Small units inherently have a high dispersion index and are subject to wide fluctuations in rate of flow, and, therefore, capacity should be proportionately increased as the size of the unit decreases. For sewage flows of 500 to 10,000 gallons per 24 hours, septic tanks are generally employed; and for flows of 10,000 to 100,000 gallons per 24 hours, Imhoff tanks are more satisfactory. For flows in excess of these, designs are based on requirements previously discussed for conventional municipal systems. Figure 128 may be employed as a guide to adequacy of design, but allowances above or below these values may be made for unusual conditions. Based upon sewage flow per 24 hours,† combined sedimentation and sludge capacities are indicated in terms of hours of sewage flow and also in gallons. For Imhoff tanks, also, the fraction of the capacity required for the sedimentation compartment is indicated in gallons.

In proportioning tank dimensions, the principles governing short circuiting or dispersion (p. 437) should be considered. Preferably,

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* Grease interceptors may be installed for large institutions where there are heavy kitchen wastes, but such interceptors require frequent cleaning and if neglected are useless and may cause a nuisance. They are not recommended for small installations.

† Storm water from roof leaders or areaway drains and any ground water drainage should be excluded from the sewage flow.

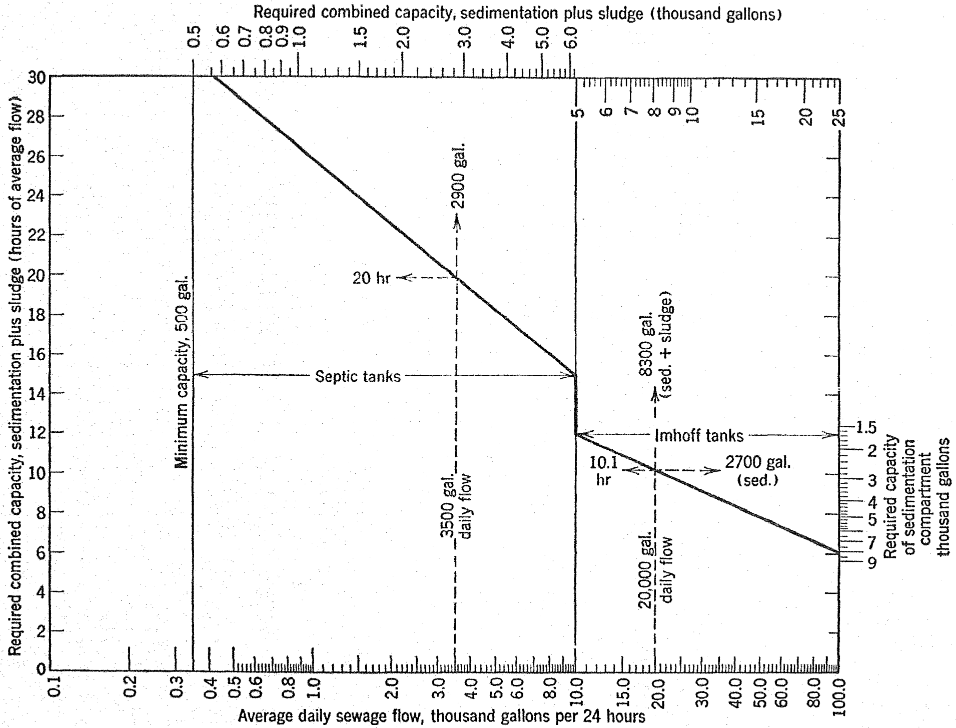

FIG. 128. Capacity requirements for septic and Imhoff tanks.

the length should be greater than twice the width, and depth below flow line at least 4 feet.

Septic and Imhoff tanks require periodic removal of sludge, but, with proper allowances in the design, in the smaller units sludge removal should be necessary only every 2 or 3 years. Usually scavengers are employed to pump or bail the contents into a tank and haul it to a suitable disposal area for burial or discharge into a municipal sewerage system. This is expensive and too frequently is neglected beyond the time required to keep the sludge accumulation from encroaching upon the sedimentation capacity or interfering with subsequent disposal of the liquid fraction. In larger installations, particularly Imhoff tanks, the unit can be constructed partially above the ground for sludge to be withdrawn by gravity to an area for burial or to a suitable drying bed.

DISPOSAL OF THE LIQUID FRACTION

In general, it is more satisfactory and economical to discharge the liquid fraction from the larger installations into a surface stream, even if further treatment beyond separation of solids is required. The small installations, ground conditions permitting, generally discharge to the ground water. The conditions governing discharge of partially treated effluents to surface streams have been fully discussed in the preceding chapters. We shall deal here primarily with the problem of disposal to the ground water.

Disposal to the ground water is dependent upon ability of the soil to absorb the liquid without ponding or overflowing on the surface of the ground. Heavy tight clay, hardpan, and rock are unsuitable, and subsurface absorption should not be attempted in such formations. Soils listed in the order of their suitability for subsurface absorption are as follows:

Coarse sand or gravel.
Fine sand.
Sandy loam or sandy clay.
Clay with considerable sand or gravel.
Clay with small amount of gravel or sand.

Soil Seepage Test. The seepage area required for any specific installation is conveniently determined from *soil seepage tests* developed by the New York State Department of Health. The tests were correlated with actual seepage systems that had failed or were about to fail after having operated successfully for approximately 20 years. Designs based upon the soil test, if properly maintained, should, therefore, operate satisfactorily for a period of 20 years.

The test is made by digging a hole one foot square into the soil formation to be used as the seepage area, filling the hole with 6 inches of water, and observing the time required for the water to seep away. Where shallow subsurface seepage trenches are employed, test holes should extend to the elevation of the proposed trench bottom; and for deep seepage pits the tests should be made in undisturbed soil at about mid-depth of the proposed pits. If soils are very dry the tests should be repeated and the slower seepage rates used. With the average time in minutes required for the water to drop one inch in the test hole (one sixth of the total time for water to seep away) the allowable loading in gallons per day per square foot of seepage area may be estimated from Figure 129.

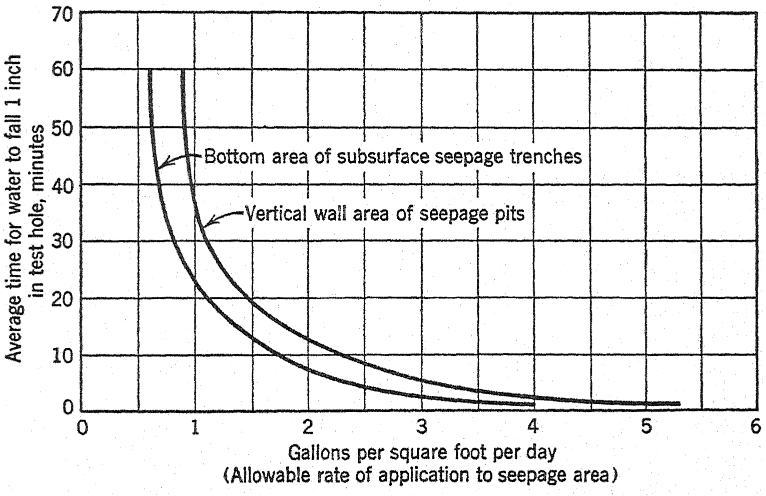

Fig. 129. Relation between soil-seepage test and required seepage area for septic- or Imhoff-tank effluent disposal.
(After N. Y. State Dept. of Health)

Shallow Seepage Trench. Two types of subsurface soil absorption systems are commonly employed, shallow seepage trenches and deep seepage pits. Wherever feasible, the shallow trench system should be used, as aerobic conditions prevail, with high biological purification and a minimum of soil clogging. The shallow seepage, well above the water table level, insures the maximum protection against contamination of the ground water. A substantial quantity of the discharge of the liquid fraction in shallow seepage trenches is lost to the atmosphere by land evaporation, and, where vegetative cover is provided, by transpiration. During warm weather months these losses may completely account for disposal of the liquid fraction, with no percolation to the ground water.

A series of shallow lateral trenches are excavated to a depth of 18 to 36 inches, depending upon the topography, and to a width ranging from 12 to 36 inches (narrow for gravel and sand, wider for less porous soils). Crushed stone or gravel (¾ to 2½ inches) to a depth of 6 inches is placed in the trench on which is laid a 4-inch open-jointed distribution tile. Stone is placed around the tile to hold it in place, covering it to a depth of about 2 inches. The trench is then backfilled with earth to the original ground level. Laterals should be spaced at least three times the width of the trench, with a minimum of 6 feet. Length of laterals should not exceed 100 feet and where feasible should be 60 feet or less. There are various arrangements of laterals, depending upon the area available, of which Figure 130 is typical. The effective seepage area is taken as the total square feet of trench bottom, and requirements are determined by soil tests. In large installations exceeding 1000 lineal feet of tile, a dosing tank and siphon should be provided to alternate the discharge between at least two separate segments of the trench area.

DEEP SEEPAGE PITS. Where adequate area is not available or where soil formation in the upper 3 feet is unsuitable or poor, but is satisfactory at lower levels (above the ground water table), recourse may be had to the less satisfactory deep seepage pit. One or more pits, 3 feet or more in diameter, at least 6 feet deep into the porous strata, lined with open-jointed dry stone walls backed with 3 or more inches of coarse gravel, and capped with a manhole and cover, are provided to receive the discharge from the septic or Imhoff tank. The pits are generally filled to the inlet flow line with the liquid which by aid of hydrostatic pressure seeps laterally into the surrounding soil through the open vertical walls. The system is completely anaerobic within the pit and extending into the lateral seepage area. The end products of anaerobic decomposition tend

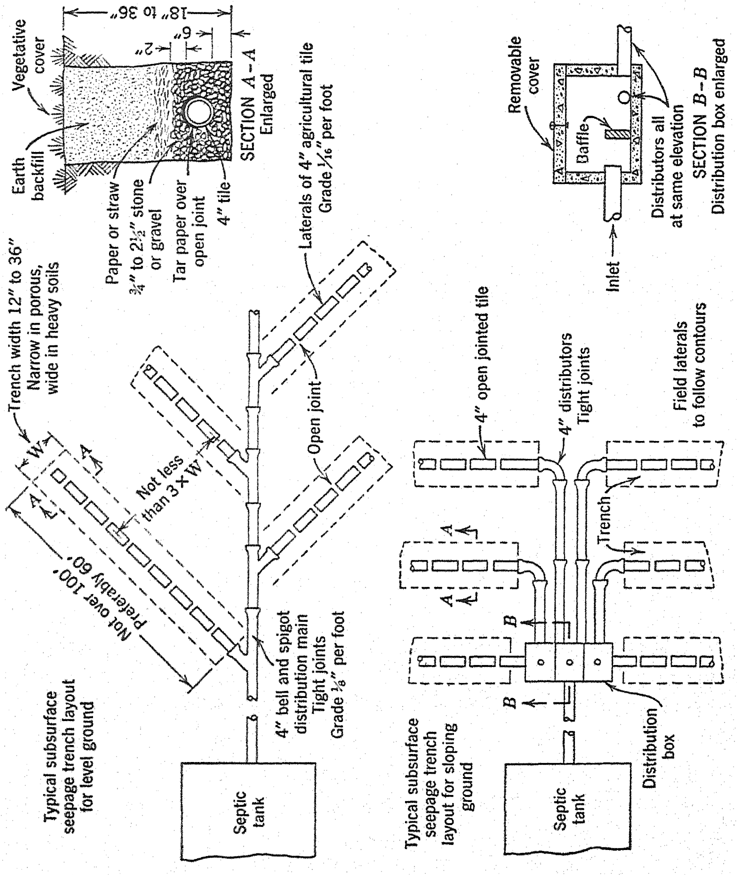

FIG. 130. Subsurface seepage trenches.

to clog the soil. It is not uncommon to have such pits back up or leach out at the ground surface. By virtue of liquid standing at considerable depth within the pit and the proximity to ground water flow, the dangers of transmission of contamination beyond the immediate confines of the pit are substantially greater than with the lightly dosed shallow trench system. Before deep seepage pits are installed, careful consideration should be given to the principles governing ground water pollution previously discussed (p. 340). The effective area of seepage pits is taken as the vertical wall area below the inlet flow line measured to the outside of the wall in contact with the soil. The area of the bottom is excluded, as it is ineffective because of accumulated sludge blanket. Requirements are based on soil tests.

ARTIFICIAL BIOLOGICAL BEDS. In tight clay or other impervious soils and where there is danger of contamination of ground water from deep seepage, it is necessary to provide a more complete treatment of septic or Imhoff tank effluent before ultimate disposal of the liquid fraction. For the small installations the subsurface intermittent sand filter may be used, providing a suitable outlet is available. Such a filter comprises 2 to 3 feet of sand placed in an excavation and covered with soil. Open-jointed 4-inch tile spaced at 6-foot centers surrounded by gravel are laid on top of the sand to distribute the tank effluent. Similarly, tile laid in trenches (filled with gravel) on the prepared bottom of the excavated impervious soil serve as underdrains. These drains terminate in a collector laid along one end of the bed. Such a combination of sedimentation and biological treatment produces an effluent of high quality. In most situations it can be safely discharged into a ditch or drain leading to a surface stream, or, if the quantity is small, it may be feasible to return it to the ground water in deep seepage pits. Subsurface filters should be designed for a rate of filtration not greater than 50,000 gallons per acre per day (1.15 gallons per square foot per day).

Where complete treatment is required for the larger establishments, intermittent sand or trickling filters of the conventional designs may be used. The trickling filter requires less area and has the advantage that small units may be glassed in or completely enclosed in a shelter, which can be made as ornamental as desired to conceal its purpose. Trickling filters, however, require greater head, and the filter effluent must receive secondary sedimentation before discharge to a water course.

THE CESSPOOL

A cesspool is a deep seepage pit into which *raw sewage* is discharged in an attempt to dispose of the solids and the liquid fraction in one operation. It is basically wrong in principle and leads to ground water pollution and unsanitary surface conditions. The features which made the deep seepage of tank effluent objectionable are greatly accentuated in the cesspool by virtue of the inclusion of the solids, grease, and fats. Except under very favorable conditions, the cesspool, after contributing to the pollution of the ground water, becomes water-tight and of no further use as a seepage device, thus reverting to the status of a septic tank, except that, since no provision has been made for overflow, it discharges on the surface. Like a septic tank, even under favorable conditions, it requires periodic cleaning, that is, removal of the accumulated sludge residue. The use of cesspools is definitely to be discouraged.

NONWATER CARRIAGE EXCRETA DISPOSAL

Where water supply under pressure is not available, the convenience and safety of modern household plumbing is replaced by the more primitive nonwater carriage systems of excreta disposal. These systems are applicable only to the small establishments, predominantly the rural home. The extent to which they are employed is disclosed by the 1940 Census of the United States which included a survey on housing conditions throughout the nation. In an analysis of these data, the U. S. Public Health Service reports* that outside of incorporated communities there are about 13 million farm and nonfarm rural homes (approximately one third of the total population) of which 8.5 million homes used outside toilets or privies, over half of which were inadequate or unsafe; and over 800,000 homes were without any toilet facilities of any kind. In addition, of the 200,000 rural schools in the United States, over one half used outside privies, many of which were unsatisfactory. If this condition prevailed in the United States as recently as 1940, after 25 years of organized effort to improve rural areas, it is not difficult to appreciate the magnitude and importance of rural sanitation on a world-wide basis.

Many devices, good and bad, have been developed and employed throughout the years. The major considerations are *simplicity* and

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* *U. S. Pub. Health Service, Pub. Health Repts.*, 59, 969, 1944.

inexpensiveness, with a minimum of reliance upon the individual for operation and maintenance. Research and experience thus far have resulted in five more or less distinctive methods, each of which, under certain conditions, has limitations and shortcomings:

The earth pit privy.
The masonry vault privy.
The L. R. S. privy.
The removable can privy.
The chemical toilet.
The bored-hole latrine.

Three primary functions common to all methods are confining of *all* excreta to a definite isolated area; exclusion of flies, insects, rodents, and other animals; and prevention of contamination of ground water employed as water supply. In addition, *convenience* and *privacy* must be provided or the fundamental objective of safe disposal will be defeated by nonuse and reversion to promiscuous disposal of excreta.

THE EARTH PIT PRIVY

The earth pit privy is a pit in the earth covered with a structure affording privacy and shelter and containing a seat with an opening into the pit. No secondary handling of liquids or solids is required. When the pit fills, the superstructure is removed to a new pit and the old one covered with earth. Considering all aspects of nonwater carriage systems, the pit privy offers the most suitable type of excreta disposal unit for the individual rural home. It is inexpensive and simple to construct and maintain and thus affords the best chance of wide adoption. If consideration is given to certain details of design, it is as safe as or safer than other types. By far, pit privies outnumber all other types in use and proportionately show a better score in sanitary disposal.

A pit of minimum capacity of 50 cubic feet should be provided for the average family, which should serve for a period of several years. The pit should be tightly sheathed for at least 3 feet below the surface to insure enclosure, but below that depth, openings to permit seepage are desirable. A suitable sill, preferably of concrete, surrounding the sheathing, insures tight enclosure at the ground level and raises the floor and superstructure. Impervious earth mounded up to the level of the top of the sill around the entire structure prevents surface water and roof drainage from entering the pit. Many designs for superstructures have been developed by state departments of health. An important feature is exclusion of flies by a tight structure with screening of all openings for ventilation and a self-closing well-fitted door. The seats should be comfortable, and one with a smaller opening should be provided for children. Both seat and lid should be hinged to permit raising for use as a urinal. A self-closing lid is not recommended, as it is not so comfortable and frequently becomes soiled or frosted and thus contaminates clothing.

The primary consideration is protection against contamination of the ground water used for well water supply. As was shown by the Fort Caswell and other research (p. 341), pit privies dug into ordinary soils (except shale and fissured rock formations) can be considered reasonably safe with respect to contamination of the ground water, provided:

1. Any ultimate seepage from the pit into the ground is into the upper strata, the zone of aeration where the natural purifying properties of the soil with aerobic oxidizing bacteria are at work in the presence of oxygen.
2. The bottom of the pit does not penetrate the water table and is kept at least 2 feet above its maximum elevation.
3. Surface drainage and excessive ground water infiltration are excluded from the pit.
4. The pit is not dosed with discharges of water or other liquids, causing a standing accumulation. (The additions of liquids from family use including night soil collected from household commodes readily evaporate or are absorbed by the soil.)

Although there is substantial evidence to indicate that a pit privy, under these conditions, is capable of confining the bacteria of intestinal origin practically to the immediate limits of the pit, it is the general practice to provide a factor of safety by locating such privies at least 50 feet from a well or other ground water supply.

THE MASONRY VAULT PRIVY

Where the ground water table is close to the surface, or the soil formation is limestone, shale, or fissured rock, or there is necessity to protect against contamination of a near-by watercourse, well, or spring, a masonry vault privy is used. Essentially, this type of privy substitutes a water-tight masonry (concrete) vault for the earth pit (Figure 131). The other features are similar to the earth pit privy except that in the vault system when capacity is reached secondary handling of the excreta is involved in the process of cleaning. For this purpose, a suitable access cleanout door or cover must be provided, usually at the rear of the vault. Vault contents must be buried or dumped into a municipal sewerage system.

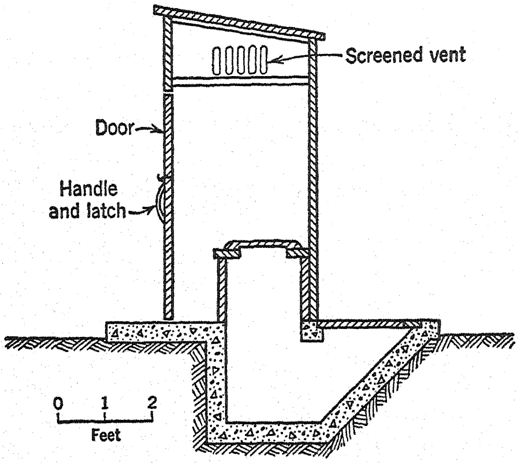

FIG. 131. Masonry vault privy.

This system, in theory, should prevent contamination of water supply sources, but in practice the safety provisions are seldom realized. Unless a high-grade reinforced-concrete structure is constructed, the vault will not be water-tight, and substantial leakage may occur. Because of cost, vaults are generally underdesigned, requiring frequent cleaning with the attendant danger of spillage. The expense of cleaning operations tends to discourage proper maintenance, with the result that surcharging takes place, and, if cleanout doors are at a low elevation, seepage may take place to the surrounding ground surface. Effectiveness of the vault privy depends upon inspection by a department of health at time of construction to insure a water-tight structure, followed by routine systematic inspections to insure proper cleaning.

THE L. R. S. PRIVY

Various modifications of the septic tank principle have been employed in privy design. These offer more complete disposal and require less frequent attention. The principle may well be illustrated by the prototype of all these *sanitary privies,* the original L. R. S. (Lumsden–Roberts–Stiles) privy developed by those three officers of the U. S. Public Health Service.* An early model, and one still excellent for use in the country home, is shown in Figure 132. It consists of two cider barrels and the connections as indicated. The first barrel is filled with water at the start, and it is important to keep it filled. During dry weather, evaporation is likely to exceed additions. The second barrel receives the overflow, clarified by sedimentation and septic digestion. It is filled with sand and provided with drainage holes at the bottom. Again, evaporation will take care of the fluid, except during rainy weather. It is even helpful to permit weeds to grow in the sand, as they assist in disposal of water by transpiration.

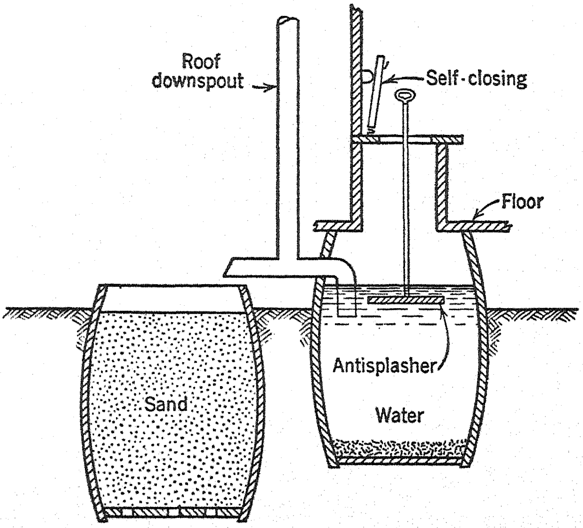

FIG. 132. L. R. S. privy.

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* *U. S. Pub. Health Service, Pub. Health Repts.,* 25, 1623, 1910.

Amplification of the principle of this biological disposal plant has led to various designs such as the *Kentucky privy,* in which the entire structure is built of concrete.

Final disposal of the privy contents must be provided for in all cases. This requires some thought, in order to avoid the very dangers which the privy is built to prevent. Shallow burial in prepared trenches is best, covering lightly with top soil. Deep burial in a pit, remote from the well, may prove adequate but is less desirable. The great advantage of biological tanks is that they require servicing much less frequently, perhaps once a year, and produce much less residue.

THE REMOVABLE CAN PRIVY

This type of privy employs a water-tight receptacle, preferably an iron can or pail, placed immediately beneath the seat for receiving deposits of human excreta. The can replaces the pit or vault, but otherwise the superstructure is similar to the pit privy. The flooring on which the can is placed should preferably be of concrete. A tight-closing door is provided in the rear for removal of the can.

This system requires daily or triweekly removal and replacement of the can. It may be operated as a *dry* can privy by keeping a pail of earth or ashes at hand to be used liberally after each visit. This plan has the advantage over the *wet* can of lessened odor and greater ease of handling.

The success of the removable can system depends upon regular reliable maintenance. It is best adapted to temporary organized camps where a responsible scavenger service can be established. Soiled cans are removed daily and hauled to a central area where facilities are available for properly cleaning the cans and for disposal of the contents by burial or discharge to a sewerage system. The liquid wastes from can washing create a problem if the disposal station does not have access to a sewerage system. The removable can system is not suitable for any but temporary camps of short duration. It is not recommended for permanent establishments and homes, as the maintenance is excessive.

THE CHEMICAL TOILET

Chemical toilets differ from privies in that they are commonly placed inside the dwelling or in a special attached shelter, whereas privies are located apart from the dwelling. They are distinctive, also, by virtue of their reliance upon a chemical to disintegrate the excreta.

A metal tank containing the chemical solution is placed in the ground, with one end directly beneath the toilet. The essential features are a vertical riser connecting the tank to the toilet, an agitator, a seat vent stack and a cleanout manhole. In some installations a drain is provided to dispose of liquid residue to a seepage pit. Generally, 125 gallons of tank capacity is provided per seat.

The chemical most frequently employed is caustic soda. A charge per seat of 25 pounds dissolved in 10 to 15 gallons of water will serve for a period of 6 to 9 months. The caustic emulsifies the solids and kills the bacteria; therefore, biological decomposition is prevented. When the excreta is properly mixed with the solution after each use by means of the agitator, there results a dark brown liquid relatively free of odor. If the caustic solution is exhausted or if the agitator is not consistently employed, odors may result from biological decomposition.

A commode type is also available employing a removable metal pail containing the chemical which is placed directly beneath the toilet seat. The capacity is about 10 gallons, and a charge of 2 pounds of caustic soda will function for a period of about 1 week. The liquefied contents are best disposed of by burial.

Where a water carriage system cannot be provided, the chemical toilet is the most convenient method for safe disposal of excreta. It is best suited to household use in cold climates or in case of sickness or invalidism. It is also excellent for summer camps, recreational areas, and small schools. Chemical toilets are, however, comparatively expensive.

THE BORED-HOLE LATRINE

Developed principally by the International Health Division of the Rockefeller Foundation as an inexpensive method of excreta disposal, the bored-hole latrine has found its widest use in the Near East, the Far East, the West Indies, the Philippine Islands, and South America. Essentially, it comprises a deep small hole bored into the ground capped with a slab in which a suitable opening has been provided for the discharge of excreta. Two distinct types are employed. In the *wet* hole type it is intended to have the latrine function as a septic tank and thus aid in the digestion of the solids, thereby prolonging its useful life. In practice, this is accomplished by extending the hole to a depth below the water table to insure at least 3 feet of water in the hole to provide a liquid medium for the anaerobic digestion of the dry solids discharged. Where the water table is more than 25 feet below the surface, the *dry* hole type must be employed. For an average family of six, the useful life of a dry hole of 16 inches diameter, 20 feet deep, is about 2 years. It is reported that a wet hole of the same dimensions in regular use was only two thirds full after a period of 8 years.

The principal elements of the bored-hole latrine are: the hole, the floor slab, the hole lining, and the shelter (Figure 133). The *hole* is made with a simple hand-boring device similar to a posthole auger. A diameter of 16 inches is about the maximum practically attainable by simple hand operation. Smaller diameters reduce capacity and the side walls tend to become fouled near the top. To protect against fly breeding, depth should not be less than 12 feet; the most practical depth ranges between 18 and 20 feet.

The *floor slabs* should be made of impervious material, preferably reinforced concrete, and, for inexpensive quantity and quality production, are best precast at a central yard. The slab is constructed so as to drain into the hole. The opening in the *squatting* type slab for the passage of excreta should be small enough to prevent a child's falling through. A rectangular slot, 4 to 5½ inches wide by 14 to 16 inches long, has proved most satisfactory. A cover block with a long handle is desirable for closing the hole when not in use. Raised slanting footrests placed on each side of the slot insure proper position for use and minimize fouling and contact with the feet.

A concrete collar extending into the hole a short distance prevents the lip of the hole from raveling and caving. If the latrine is located indoors or in an attached lean-to, the collar should extend above the ground to the floor level, sealing in the hole. For outdoor installations, the floor slab should be raised above the ground and earth mounded to drain surface waters and prevent flooding of the latrine during heavy rainfall.

Where soils such as fine sand are inclined to cave, a *lining* or casing, usually of local materials such as wooden hoops or basket weave bamboo, is inserted in the hole to support the side walls. In stiff soils such as clay a lining is not necessary.

A *shelter* built of local materials is usually placed over the latrine located outdoors to afford privacy and protection against the elements. Consideration should be given to adequate ventilation, and if possible, fly proofing. Frequently bored-hole latrines are built inside the dwelling or house, or in a lean-to attached to the house.

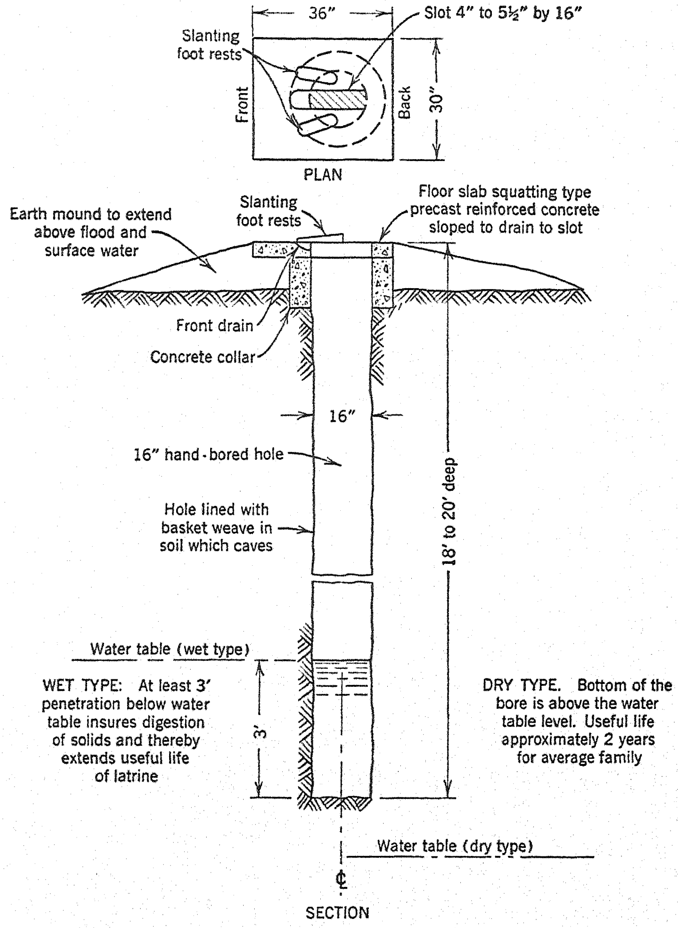

Fig. 133. The bored-hole latrine.

Because of penetration or proximity of water table, locate as far as feasible from wells; not less than 150 ft. and not in the path of ground-water flow.

In the discussion of principles of ground water pollution (p. 343) it was shown that excreta disposal pits which penetrate the ground water table are inherently more dangerous in the transmission of pollution than are shallow pits, the bottoms of which are 2 feet above the maximum water table level. For this reason, the deep bored-hole latrine must be carefully located in relation to wells.

However, this type of latrine has advantages which, under certain conditions, warrant its use, particularly where poverty and primitive living conditions prevail. It is simple and inexpensive to construct and maintain, and the design is particularly adaptable to the habits of people of certain areas of the world. The depth insures a minimum of odor nuisance and removal of excreta from the range of flies, insects, and rodents, a factor where adequate sheltering and screening are not economically feasible. In contrast to the frequent reconstruction required for shallow pit privies, the long useful life of the septic, deep bored-hole latrine offers a semipermanent solution to the problem of disposal of excreta where poverty and indifference are primary factors.

The Water Contact—Rural Water Supply

SOURCES

Ground water offers the most satisfactory source of water supply for the rural establishment, principally because it is the only source that can be used with safety without treatment. Sources that require treatment prior to use are secondary in choice, as skilled operation and proper maintenance cannot be depended upon to the same degree as in the organized and supervised municipal systems. Safety demands, therefore, the selection of a source of water supply that is inherently of high quality and naturally protected, with a minimum of dependence upon artificial barriers and the human element.

PRIORITY SOURCES

With these criteria as a guide the sources, arranged in order of priority are:

Artesian ground water.

Phreatic ground water with a deep water table overlaid with homogeneous fine soil formation.

Artesian springs derived from sand formations, overlaid with impervious formations.

Phreatic ground water with relatively shallow water table, but overlaid with homogeneous fine soil formation over 10 feet deep.

Gravity springs from homogeneous fine soil formations, the intake areas of which have a deep water table.

Rain water collected from roofs of buildings and stored in a watertight cistern.

The artesian waters have high natural protection: first, because they are under hydrostatic pressure, and therefore, the flow is outward and pollution cannot percolate inward; second, because the impervious confining cover is an effective seal against percolation from above. Artesian springs, however, have a point of weakness in their exposed surface outlet. Other ground sources which are derived from phreatic water and which, therefore, are not under hydrostatic pressure depend upon the thickness and fineness of the soil cover above the water table. Homogeneous fine formations act as good filtering devices, whereas shallow coarse cover may allow penetration of pollution to the water table. From the principles of movement of ground water pollution (p. 341), the danger zone is at or near the surface of the water table level.

Where ground water cannot be obtained, the only inherently safe source is rain water collected from roofs. This source is very limited in quantity and, although, generally safe bacteriologically, may develop objectionable tastes and odors from storage.

DOUBTFUL SOURCES

The following sources should be regarded as *doubtful* and used only when water cannot be derived from any of the priority sources or when those sources are known to be polluted by improper sewage disposal; doubtful sources should not be used except after very careful sanitary survey reveals them to be safe, or unless treatment is provided:

Phreatic ground water with water table less than 10 feet below the ground level.

Phreatic ground water or springs derived from shale or fissured rock formations.

Ground water or springs derived from cavernous limestone formations.

All surface waters, streams, lakes, ponds, or surface water storage reservoirs.

Inherently, the doubtful sources are always potentially subject to serious pollution, as the natural protection is weak. Fissured or cavernous rock formations do not offer natural filtration and, hence, may often carry pollution in their channels from distant points. All surface water sources, even so-called virgin waters, must be regarded as unsafe unless protected by chlorination at least; and this means treatment, with all that implies in respect to reliable operation.

QUANTITY

The quantity of rural water supply required varies with the size and type of establishment. This was discussed under rural sewage disposal, and since sewage is actually the spent water supply, Table 56 (p. 618), may be used as a guide to quantity requirements. There are some modifying factors which should be taken into consideration for the rural establishment, that is, additional water requirements for livestock, irrigation, and, in some instances, fire protection. For such purpose the recommendations of the Joint Committee on Rural Sanitation may serve as a guide.*

Livestock	Normal Gal per Day
Per horse, mule, or steer	12
Per dairy cow (drinking only)	15
Per dairy cow (drinking and servicing)	35
Per hog	4
Per sheep	2
Per 100 chickens	2
Per 100 turkeys	7

In the development of rural water supply, adequacy of quantity has a direct public health significance, because where water is deficient, beneficial use is curtailed or there is the potential danger of use of unprotected auxiliary sources. Too frequently the initial installation ignores the many beneficial uses, and the systems for small installations are underdesigned.

TYPES OF SYSTEMS

Rural water supply can conveniently be divided into two general systems, *pressure* and *nonpressure*.

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* *U. S. Pub. Health Service, Suppl. Pub. Health Repts.,* **185**, 1945.

THE PRESSURE SYSTEM

The pressure system is by far the more satisfactory, as it permits the installation of safe and convenient modern plumbing throughout the establishment or home. The complete system involves a source of supply, a storage tank, either elevated or hydropneumatic, and a pipe system to connect the source of supply with the storage tank and pressure distribution lines leading from the storage to the various units to be served. Ordinarily, the distribution pipes for small systems are threaded galvanized iron or steel, although, if the water is highly corrosive, it may be advisable to use the more expensive brass or copper. Heavy-bodied cast iron is available for sizes 2 inches and larger. Due allowance should be made for friction losses in selecting pipe sizes, or poor pressure may result at remote locations, or the delivery may be poor if water is drawn simultaneously at several locations. Table 57 serves as a guide for small installations.

TABLE 57

Quantity of Water Delivered With a Loss of Head of 30 Ft Per 1000 Ft of Pipe*

Pipe Size, In.	Water Delivery, Gal per Min
1	5
1½	15
2	25
2½	50
3	80
4	160

* Head loss is proportional to length, that is, 1-in. pipe, 500 ft, delivery 5 gal per min, would have a head loss of 15 ft.

In the distribution system, precaution should be taken that no cross connections, auxiliary intakes, or piping arrangements are made whereby unsafe or questionable water sources can be discharged or drawn into the domestic water supply. Also, all water outlets into tanks and other fixtures should be placed above the overflow level to prevent any possibility of back siphonage of polluted water into the water supply. No direct connections should be made between the sewer lines and the water lines (see p. 375).

In the event the source of supply is at a high elevation such as a spring, the storage tank can be integral with the development of the spring, and no pumping is required. Figure 134 shows a typical spring development.

Generally, the source is a well, and, therefore, a pump and driving unit (windmill, gas engine, or electric motor) is essential.

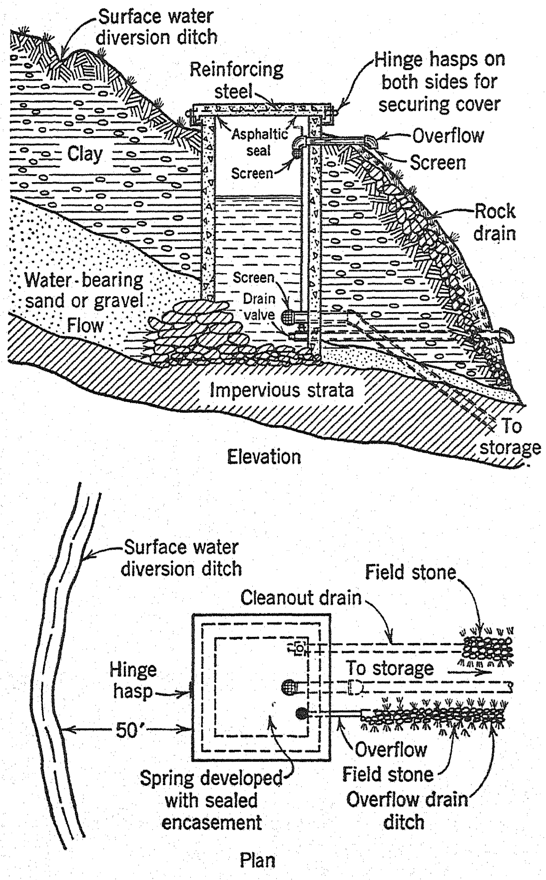


FIG. 134. Typical spring development.
(After U. S. Public Health Service)

A highly desirable feature of the pressure system is that without inconvenience or excessive cost the source of supply can be at a remote location from the establishment and, therefore, at a safe distance from the sewage disposal system (Figure 135). The development of wells and ground water supplies has been discussed (p. 353).

For large rural installations, surface water sources may be used and treatment provided. In such instances the problems are similar to those discussed for municipal systems.

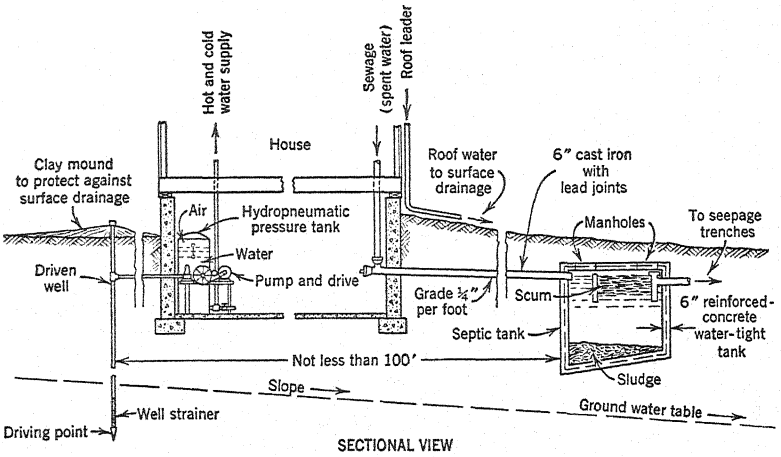


FIG. 135. Typical arrangement, showing relation between pressure-water-supply and sewage-disposal systems.

THE NONPRESSURE SYSTEM

The nonpressure system comprises a source of supply but no distribution system. Water is carried to the household in buckets or hauled in larger containers. The supply is generally a spring, well, or cistern, with a hand pump. The fact that water must be carried generally results in location of the source near the house and in many cases at an unsafe distance from the privy or barnyard. The necessity for handling the water and the use of containers and dippers introduce many opportunities for contamination, even though the source may be satisfactory. The old shallow well with bucket and windlass may be picturesque, but is generally dangerously contaminated. A properly constructed driven or drilled well equipped with a hand pump is much safer (see Figure 136 and Figure 137).

RELATION OF WATER SUPPLY TO SEWAGE DISPOSAL

Water supply must always be considered in relation to disposal of sewage. The principles of ground water pollution are not, as yet, fully defined, and so many modifying factors are involved for each situation that arbitrary distances between a water source and a source of contamination cannot be specified. Accordingly, reliance is placed upon the *rule of expediency,* and sources of water supply are removed as far from sources of contamination as is practicably feasible.

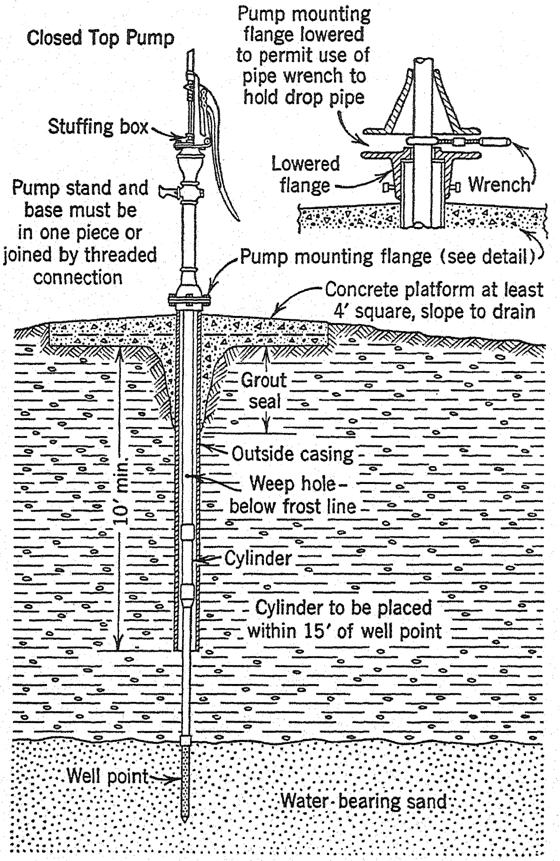


FIG. 136. Typical driven well.
(After U. S. Public Health Service)

The major factors in locating the ground water source are: location and type of sewage disposal system, type of ground water development, natural hydraulic gradient of the water table, extent of the cone of the depression formed in the water table due to pumping, and the characteristics of the water-bearing formation and overlying soil strata. Only a trained and experienced public health engineer is competent to evaluate these factors and reach a reliable conclusion as to the degree of safety for each combination of circumstances. As a starting point in such consideration, the minimum distances set forth in Table 58 represent seasoned practical judgment based on research and experience.

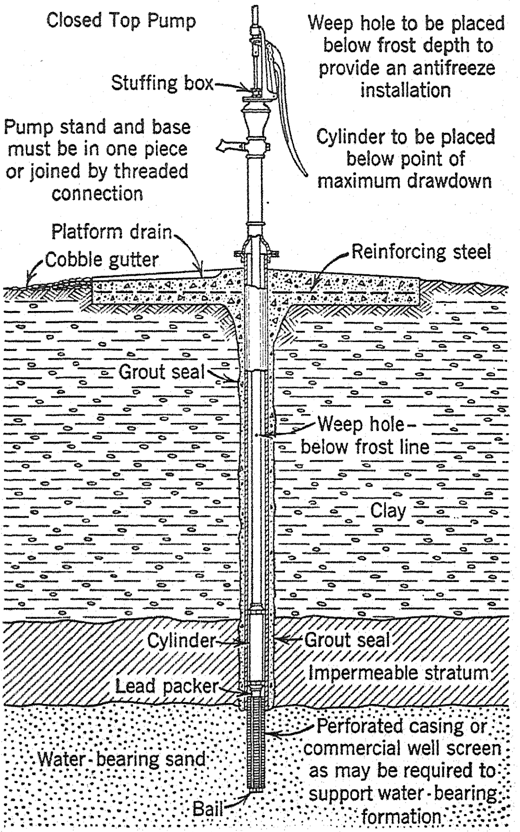


FIG. 137. Typical drilled well.
(After U. S. Public Health Service)

Sewage disposal devices should never be located above a source of water supply such that the water supply would be in the direct

TABLE 58

MINIMUM HORIZONTAL DISTANCE BETWEEN SOURCE OF WATER SUPPLY AND SOURCE OF CONTAMINATION

Where Source of Water Supply is not in the Path of Ground Water Flow Below Source of Contamination.

Conditions.	Minimum Distance, Ft
Pit privies	50
Deep seepage pits, cesspools or bored-hole latrines	150
(Shallow wells should not be used in conjunction with these sewage disposal systems)	
Subsurface seepage trenches	100
(If casing of drilled well extends water-tight for a depth of 50 feet)	50
Septic or Imhoff tank or sewers	50
Cattle or stock pasture	100
Barnyard drainage	150
Surface, storm, or flood water drainage	50

path of surface drainage. Surface contour however gives little assurance of the direction of flow of the ground water. In this connection, there is always the possibility of alteration of the normal path of flow by heavy pumping of the well. This induces a deep cone of depression in the water table which may cause pollution to travel toward the well even though the well is outside the normal path of ground water flow.

Regardless of horizontal distances from sources of contamination, a minimum vertical coverage of 10 feet of fine homogeneous soil formation is essential for protection against vertical penetration of surface pollution. If the soil is coarse or cratered, deeper vertical coverage is necessary.

DISINFECTION BEFORE USE

In any installation or repair of a water supply, pressure or non-pressure system, all parts, wells, springs, cisterns, tanks, piping systems, and pumps should be thoroughly chlorinated before use. A chlorine solution, sufficient to provide from 50 to 100 parts per million available chlorine should be applied and held or circulated within the units for a period of 12 hours, followed by a thorough flushing. A check on quality should be made by bacteriological examination.

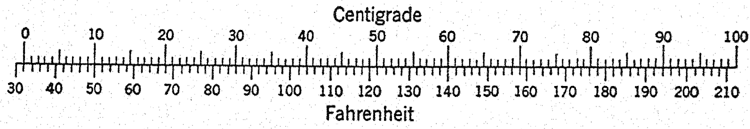
APPENDIX

CONVERSION OF UNITS

Multiply any numerical value, expressed in units A, by the corresponding factor F, to convert the value into units B. Employ the reciprocal factor $1/F$ for the reverse process.

A	B	F	$\frac{1}{F}$	$\log F$
		Lengths and Areas		
Inches	Centimeters	2.540	0.3937	0.4048
Feet	Centimeters	30.48	0.03281	1.4840
Miles	Feet	5280	1.894×10^{-4}	3.7226
Miles	Kilometers	1.609	0.6214	0.2066
Square inches	Square centimeters	6.452	0.1550	0.8097
Square feet	Square meters	0.0929	10.76	$\bar{2}.9680$
Square miles	Square feet	2.787×10^{7}	3.587×10^{-8}	7.4453
Square miles	Acres	640	1.562×10^{-3}	2.8062
Square miles	Hectares	259	3.861×10^{-3}	2.4133
Acres	Square feet	43,560	2.296×10^{-5}	4.6391
Acres	Hectares	0.4047	2.471	$\bar{1}.6071$
		Volumes		
Cubic feet	Cubic meters	2.832×10^{-2}	35.31	$\bar{2}.4521$
Cubic feet	Gallons	7.481	0.1337	0.8740
Gallons	Cubic meters	3.785×10^{-3}	264.2	$\bar{3}.5781$
Acre-feet	Million gallons	0.3259	3.068	$\bar{1}.5131$
		Velocities and Rates		
Feet per second	Miles per hour	0.6818	1.467	$\bar{1}.8337$
Feet per second	Kilometers per hour	1.097	0.9116	0.0402
Feet per minute	Miles per hour	0.01136	88.00	$\bar{2}.0555$
Cubic feet per second	Million gallons per day	0.6464	1.547	$\bar{1}.8105$
Cubic feet per second	Gallons per minute	448.9	2.228×10^{-3}	2.6521
Million gallons per acre	Cubic meters per hectare	9353	1.069×10^{-4}	3.9709
Million gallons per acre per day	Gallons per square foot per minute	1.594×10^{-2}	62.73	$\bar{2}.2025$
Inches (rainfall) per year	Gallons per day per square mile	4.758×10^{4}	2.101×10^{-5}	4.6775

A	B	F	$\frac{1}{F}$	$\log F$
Weights and Pressures				
Pounds	Grams	453.6	2.204×10^{-3}	2.6567
Pounds	Grains	7000	1.429×10^{-4}	3.8451
Ounces (avg.)	Grams	28.35	3.527×10^{-2}	1.4526
Grains	Grams	6.480×10^{-2}	15.43	$\bar{2}.8116$
Pounds (water)	Cubic feet	1.602×10^{-2}	62.43	$\bar{2}.2047$
Pounds (water)	Gallons (U.S.)	0.1198	8.346	$\bar{1}.0785$
Pounds (water)	Gallons (Imp.)	0.1000	10.00	$\bar{1}.0000$
Pounds per square inch	Kilograms per square meter	703.1	1.422×10^{-3}	2.8470
Pounds per square inch	Feet (water)	2.307	0.4334	0.3631
Pounds per square inch	Inches (mercury)	2.036	0.4911	0.3088
Pounds per square inch	Atmospheres	6.804×10^{-2}	14.70	$\bar{2}.8328$
Density and Concentrations				
Grams per cubic centimeter (s.g.)	Pounds per cubic foot	62.43	1.602×10^{-2}	1.7954
Grams per cubic centimeter (s.g.)	Pounds per cubic inch	3.613×10^{-3}	27.68	$\bar{2}.5579$
Parts per million	Milligrams per liter	1.0	1.0	0.0000
Parts per million	Pounds per million gallons	8.347	0.1198	0.9215
Parts per million	Grains per gallon (U.S.)	5.842×10^{-2}	17.12	$\bar{2}.7666$
Parts per million	Grains per gallon (Imp.)	7.000×10^{-2}	14.29	$\bar{2}.8451$
Temperature and Heat (see scale)				
[Temp. (°C) + 273]	Temp. (absolute)	1	1	0.0000
[Temp. (°C) + 17.78]	Temp. (°F)	1.800	0.5556	0.2553
[Temp. (°F) − 32.0]	Temp. (°C)	0.5556	1.800	$\bar{1}.7447$
Btu	Kilogram-calories	0.2520	3.968	$\bar{1}.4014$
Time				
Day	Minutes	1,440	6.944×10^{-4}	3.1584
Day	Seconds	86,400	1.157×10^{-5}	4.9365



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